Appendix B: The Future of Earth Remote Sensing Technologies

This appendix examines technology issues associated with the research, development, and acquisition of future U.S. civilian Earth observation systems. It begins with a review of EOS science priorities and the effect of EOS program restructuring on the development of advanced remote sensing technology. This appendix also discusses ongoing efforts to develop affordable and/or less risky versions of several large EOS "facility" instruments that were deferred or deleted during program restructuring. Next, the appendix briefly summarizes sensor platform and design considerations, including design compromises and tradeoffs that must be made to match a particular mission with an appropriate sensor and platform combination.

Finally, this appendix explores the state of the technical ' 'infrastructure' for future space-based remote sensing efforts. Researchers interviewed by OTA generally believed that planned efforts in technology development at the component level were sufficient to develop next-generation sensors. However, they were less sanguine in their assessment of efforts for ''engineering' development, for example, the packaging and prototyping of integrated, space-qualified sensors. Engineering development, while not as glamorous as basic science, is essential if the United States wishes to reduce the size, weight, and cost of space-based sensors and platforms. As discussed below, engineering issues also enter into debates over the maturity of proposals to develop new small satellites.

Introducing advanced technologies in Earth remote sensing systems raises several issues, including the role of government in identifying and promoting R&D for Earth remote sensing; and the timing of the introduction of new technologies in operational remote sensing programs. NOAA's problems with the development of its GOES-Next environmental satellite system brought the latter issue to congressional attention (see ch. 3). The issue has also arisen in connection with the selection of sensors for Landsat 7,now scheduled for launch in 1997.

Finding a balance between the risks and potential benefits of technical innovation is a particular problem in satellite-based remote sensing systems because these systems are characterized by long lead times and high costs. Payload costs are a sensitive function of satellite weight and volume.[1] In principle, satellite weight and volume might be reduced by incorporating advanced technologies, now in development, with next generation spacecraft, However, in practice, proposed new instrument technologies are often at an early stage of development and have not demonstrated the ability to provide the stable, calibrated data sets required for global change research. In addition, they may not have the fully developed data processing systems and well-understood data reduction algorithms required to transform raw data into useful information.[2] The requirements for stability, calibration, and well-developed data analysis systems are particularly evident in long-term monitoring missions.

Historically, programs have attempted to minimize risk in satellite programs by introducing new technologies in an evolutionary reamer, typically only after subjecting them to exhaustive tests and proving designs in laboratory and aircraft experiments.[3] Although experts generally agree on the desirability of accelerating this relatively slow process, they do not agree on the risk that would be associated with a change in the traditional development cycle.[4] **The risks in developing a new sensor system have two components: the technical maturity of component technologies (e.g., the detector system), and the design maturity. A particular design that has not been used before may be a relatively risky venture for an operational program, even if it is based on proven technology.**[5]

Efforts to develop and flight-test emerging technologies have been limited by a number of factors, including budget constraints; scientific disputes over the merits of specific proposals; intra-agency and inter-agency rivalries; and the absence of a coherent strategy for remote sensing, developed within the executive branch and supported by the relevant authorization and appropriation committees of Congress. **These problems are embedded in an issue of even greater concern to global change researcher-whether it will be possible to sustain institutional commitments, including those from NASA, DOE, and DoD, for periods of time that are long compared to the time for changes in the executive branch and in Congress.** Without such a commitment, much of the current effort to develop strategies and instrumentation to monitor important climatological variables could be wasted.

Technology and the Restructured Earth Observation System

In conjunction with its international partners, the United States plans a program of Earth observation systems to provide, by the early years of the next century, comprehensive monitoring of Earth resources, weather, and natural and human-induced physical and

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1 U.S. Congress, Office of Technology Assessment, *Affordable Spacecraft: Design and Launch Alternatives,* OTA-TM-ISC-60 (Washington, DC: U.S. Government Printing Office, September 1990).

2 The complex analysis required to measure the Earth's radiation budget (discussed below) provides an illustrative example.

3 For example, in the 1960s and 1970s NASA and NOAA had a successful 3-stage process for instrument development: (1) *technology development* was supported via an Advanced Applications Flight Experiments (AAFE) program for new instrument concepts, usually leading to tests on aircraft flights, (2) *research space flights* were provided for promising instruments graduating from AAFE, on the Nimbus satellite series, with flights every 2 or 3 years, (3) *operational satellites* carried instruments selected from those tested via the first two stages.

4 A phased development cycle has traditionally been used to procure operational systems. The steps in this cycle can be grouped as follows:

Phase A—Study Alternate Concepts

Phase B—Perform Detailed Design Definition Study (manufacturing concerns addressed in this stage)

Phase C—Select Best Approach/Build and Test Engineering Model

Phase D-Build Flight Prototype and Evaluate on Orbit

This approach should be contrasted with a ''skunk-works' approach, which omits some of these steps. Historically, the skunk-works approach has usually been thought more risky than the methodical approach. As a result, it has been used mostly for demonstrations and experiments.

5 Recognizing this problem, the Advanced Research Projects Agency (ARPA) has proposed several advanced technology demonstrations (ATDs) on small satellites that, if successful, would rapidly insert technology and shorten acquisition time for larger satellites. These demonstrations would couple innovative sensor design with a scalable high-performance common satellite bus that would employ a novel "bolt-on" payload-bus interface.

chemical changes on land, in the atmosphere, and in the oceans (see chs. 3-5). NASA's Earth Observing System of satellites is the centerpiece of NASA's Mission to Planet Earth. NASA has designed EOS to provide 15 years of continuous high-quality data sets related to research priorities recommended by the Intergovernmental Panel on Climate Change (IPCC) and the Committee on Earth and Environmental Science (CEES) of the Federal Coordinating Council for Science, Education, and Technology (FCCSET) (table 5-1). To achieve 15-year data sets, each of two EOS polar platforms, with a design life of 5 years, would be flown three times. Most scientists believe an observation period of 15 years is long enough to observe the effects of climate change resulting from the sunspot cycle (11 years), several El Nino events, and eruptions of several major volcanoes. It should also be possible to observe some effects of deforestation and other large-scale environmental changes. Scientists are less certain whether 15 years is long enough to distinguish the effects of anthropogenic greenhouse gases on Earth's temperature from natural background fluctuations. Ecological studies of the health and migration of terrestrial systems also require longer continuous records (on the order of 20-50 years).

Intermediate-size, polar-orbiting satellites are the principal EOS platforms for sensors gathering global change data.[6] Measurements for MTPE can be broadly divided into two types:

1. Long-term monitoring-to determine if climate is changing, to distinguish human-induced from naturally induced climate change, and to determine global radiative forcings and feedbacks (box B-1).
2. Mechanistic or "process" studies-detailed analysis of the processes that govern phenomena ranging from the formation of the Antarctic ozone hole to the gradual migration of tree species.[7]

Global change researchers disagree over whether the EOS program as currently configured is optimally designed to perform these different missions and whether the EOS program will address the most pressing scientific and policy-relevant questions. EOS program officials point to repeated and extensive reviews by interdisciplinary panels in the selection of instruments and instrument platforms as evidence that their program is properly structured. Program officials also note that payload selection panels followed priorities set by members comprised mostly of theorists who would be the users of data, rather than instrument builders hoping for approval of a particular mission. Nevertheless, some Earth scientists express concern that:

- The limitations of satellite-based platforms will prevent process-oriented studies from being performed at the level of detail that is required to address the most pressing scientific questions;
- Continuous long-term (decadal time-scale) monitoring is at risk, because of the high-cost, long lead times, and intermittent operations that have historically characterized design, launch, and operation of large multi-instrument satellite platforms.

According to this view, a more "balanced" EOS program might have greater support for small satellites and a more balanced USGCRP program might include greater support for groundbased measurement pro-

[6] These arc multi-instrument satellites and are relatively expensive. For example, NASA estimates that total hardware development costs for the EOS AM-1 satellite and its sensors will approach $800 million. This figure does not include launch costs, which are expected to be $100150 million, or ground segment and operations costs. EOS AM-1 includes the U.S.-developed MODIS, MISR, and CERES instruments and the foreign-supplied ASTER and MOPITT instruments (provided at no cost to build to the United States).

The cost of building follow-ons m the AM series would be substantial} less as much of the initial cost is associated with nonrecurring instrument and spacecraft bus design and development costs and one-time acquisition of ground support elements. Savings of 50 to 70 percent may be possible, depending on the acquisit ion time-schedule. EOS' PM series of multi-instrument satellites will not be a copy of the AM series. (Costs for PM-1 are expected to be similar, but somewhat lower, than for AM-1. Follow-ons to the PM series may not be as expensive as follow-ons m the AM-l series because most of the PM instruments are repeated.

[7] Scientists make no clear delineation between process studies and monitoring studies. In general, global change researchers use the term "process study" to refer to short-term less costly, and more focused experiments that aim to elucidate the details of a particular mechanism of some geophysical, chemical, or biological interact ion. The distinction is least useful for studies of the land surface, which may require years or more of study (for example, studies of terrestrial ecosystems may require a decade or more of observation to study a particular Process such as migration of tree species).

Box B-1-Climate Forcings and Feedbacks

Climate forcings are changes imposed on the planetary energy balance that alter the global temperature; radiative feedbacks are changes induced by climate change. Forcings can arise from natural or anthropogenic causes. Examples of natural events are the eruption of Mt. Pinatubo in June 1991, which deposited sulfate aerosols into the upper atmosphere, and changes in solar irradiance, which scientists believe may vary by several tenths of a watt/m^2 per century (the Earth absorbs approximately 240 watts/m^2 of solar energy). Examples of anthropogenic forcings appear in the table "Human Influence On Climate," below. At present, the dominant climate forcing appears to be the increasing concentration of greenhouse gases in the atmosphere.

The distinction between forcings and feedbacks is sometimes arbitrary; however, forcings can be understood as quantities normally specified in global climate model simulations, for example, $C0_2$ amount, while feedbacks are calculated quantities. Examples of radiative forcings are greenhouse gases ($C0_2$, CH_4, CFCS, N_2Q 0_3, stratospheric H_20), aerosols in the troposphere and stratosphere, solar irradiance, and surface reflectivity. Radiative feedbacks include clouds, water vapor in the troposphere, sea-ice cover, and snow cover. For example, an increase in the amount of water vapor increases the atmosphere's absorption of long-wave infrared radiation, thereby contributing to a warming of the atmosphere. Warming, in turn, may result in increased evaporation leading to further increases in water vapor concentrations.

The effects of some forcings and feedbacks on climate are both complex and uncertain. For example, clouds trap outgoing, cooling, longwave infrared radiation and thus provide a warming influence.[1] However, they also reflect incoming solar radiation and thus provide a cooling influence. Current measurements indicate t hat the net effect of clouds is a cooling one. However, it is uncertain if the balance will shift in the future as the atmosphere is altered by the accumulation of greenhouse gases.

An example of a radiative forcing whose effect on climate is uncertain is ozone. The vertical distribution of ozone (O_3) affects both the amount of radiation reaching the Earth's surface and the amount of re-radiated infrared radiation that is trapped by the greenhouse effect. These two mechanisms affect the Earth's temperature in opposite directions. Predicting the climate forcing due to ozone change is difficult bemuse the relative importance of these two competing mechanisms is also dependent on the altitude of the ozone change. Calculations by Dr. James Hansen of the Goddard Institute for Space Studies indicate that ozone loss in the upper stratosphere warms the Earth's surface because of increased ultraviolet heating of the troposphere; ozone addition in the troposphere warms the surface moderately; and ozone loss in the tropopause causes a strong cooling because the low temperature at the tropopause maximizes the ozone's greenhouse effect.[2]

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1 V. Ramanathan, Bruce R. Barkstrom, and Edwin Harrison, "Climate and the Earth's Radiation Budget," *Physics Today, vol.* **42, No. 5, May 1989, pp. 22-32.**

2 The troposphere, or lower atmosphere, is the region of the atmosphere where air is most dense and where most weather occurs. By this definition, the troposphere extends from the surface to altitudes of roughly 30,000-50,000 feet. In dear sky, the troposphere is largely transparent to incoming solar radiation, which is absorbed at the Earth's surface.

The temperature of the atmosphere falls steadily with increasing altitude throughout the troposphere (normally several 'F per 1,000 feet altitude). The heat transfer by turbulent mixing and convection that results from this variation, the coupling of the Earth's rotation to the atmosphere, and latitudinal variations in temperature are responsible for the development and movement of weather systems. Troposphere temperatures reach a minimum at the tropopause, the boundary between the troposphere and the stratosphere, and then remain approximately constant through the lower stratosphere. The temperature rises again in the upper stratosphere. The tropopause can reach temperatures as low as 185 K (-126 oF) in the polar winter.

Human Influence On Climate

Fossil Fuel Combustion

- CO_2 and N_2O emission (infrared (IR) trapping)
- CH_4 emission by natural gas leakage (IR trapping)
- NO, NO_2 emission alters O_3 (ultraviolet absorption and IR trapping)
- Carbonaceous soot emission (efficient solar absorption)
- SO_2-Sulfate emission (solar reflection)

Land Use Changes

- **Deforestation (releases CO_2, increases albedo, and increases snow albedo feedback)**
- **Regrowth (absorbs CO_2, decreases albedo, and decreases snow albedo feedback)**
- **Biomass burning (releases CO_2, NO, NO_2, and aerosols)**
- Landfills (releases CH_4)

Agricultural Acfivity

- Releases CH_4 (IR trapping)
- **Releases N_2O** (IR trapping)

/ndustrial Activity

- Releases CFCS (IR trapping and leads to ozone destruction)
- Releases SF_6, CF_4, and other ultra-longlived gases (IR trapping virtually forever)

SOURCES: J. Hansen, W. Rossow, and 1. Fung, "Long-Term Monitoring of Global Climate Forcings and Feedbacks," Proceedings of a Workshop held at NASA Goddard Institute for Space Studies, Feb. 3-4, 1992; and Johan Benson, "Face to Face," Interview with James Hansen, Aerospace *America,* **April 1993, pp. 6-11. Table on human influence on climate adapted from Dr. Jerry D. Mahlman, "Understanding Climate Change,"' Draft Theme Paper, prepared for Climate Research Needs Workshop, Mohonk Mountain House, Nov. 8, 1991.**

grams, including ocean measurement systems, and alternative sensor platforms, such as long-duration, high-altitude unpiloted air vehicles.

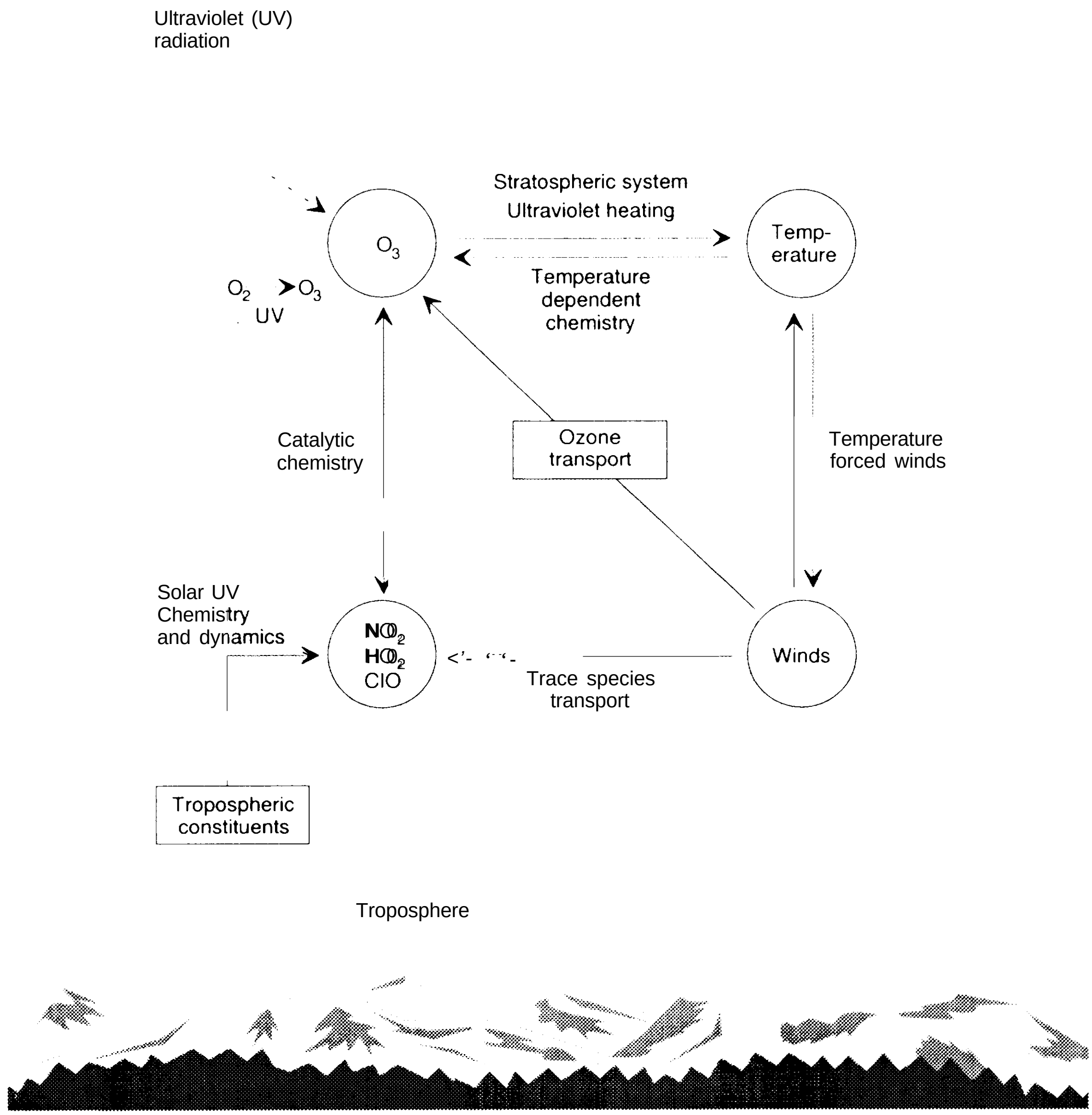
The USGCRP and National Space Policy Directive 7 have assigned the lead role in enabling global observations from space to NASA (see ch. 2). Greater support for the non-space-based elements of the USGCRP would provide important data that would complement or correlate data derived from space-based platforms. Officials from the USGCRP, NASA, and NOAA who attended a February 1993 OTA workshop were unanimous in their belief that relatively modest additions of funds could produce substantial increases in scientific output.[8]

In restricting the EOS program (see ch. 5) NASA has sought to emphasize those global change issues thought to be most in need of improved scientific understanding to support national and international policymaking activities. This has affected both mission priorities and instrument selection. **The restructured program's first priority is acquiring data on global climate change.** As a result, NASA has deferred missions designed to improve scientific understanding of the middle and upper atmosphere and of solid Earth geophysics. Instruments affected by this decision include new sensors for very high-resolution infrared, far-infrared, and submillimeter wave spectroscopy.

Deferral of instruments to monitor solid Earth physics, which includes the study of crustal and ice sheet movements, was based on the relative unimportance of these processes to global climate change. A

[8] For example, several officials agreed that increases in USGCRP budgets on the order of $100 million per year for correlative measurements would ' 'double scientific output. Greater support for complementary non-space-based elements of the USGCRP could be provided either by redirection of already tight NASA budgets, from greater support for the USGCRP within the DOE, DoD, and other relevant departments and agencies, or from increases in USGCRP budgets. EOS program officials are emphatic in stating that their already reduced budget has little flexibility to accommodate further reprogramming. A discussion of this and related issues will appear in a forthcoming OTA background paper, ''EOS and USGCRP: Are We Asking and Answering The Right Questions?'

Figure B-l—Physical Processes Operating In the Stratosphere



The arrows show interactions between imposition and atmospheric renditions. Maintenance of the stratospheric ozone layer, which shields terrestrial life from solar UV radiation, is of prime concern.

SOURCE: "Protecting the Ozone Layer," *Energy and Technology,* **May, June 1990, p. 50.**

different reasoning may account for the decision to defer instruments to monitor stratospheric chemistry and, in particular, ozone depletion (figure B-l). The United States and other nations had already agreed to steps that would phase out the use of ozone-depleting chlorofluorocarbons (CFCS). Furthermore, even without the EOS instruments, NASA officials could anticipate improvements in understanding of upper atmosphere chemistry and the mechanisms for ozone depletion as data from UARS, a precursor satellite to EOS, was combined and analyzed with data from groundbased, and in-situ balloon and aircraft measurements.

However, assessment of the success of efforts to stabilize ozone reductions may be hampered by the deferral of instruments to monitor the upper atmosphere. In addition, elimination of missions that might provide a detailed understanding of the fundamental processes that are causing ozone depletion in the lower stratosphere increases the risk that the United States and other countries will be unprepared to respond to future "surprises" with respect to ozone depletion.[10] Similarly, detailed process studies are necessary to measure the sources and sinks of carbon dioxide and other greenhouse gases. Without this knowledge, regulative and mitigative actions cannot be made with high confidence that the desired effect (for example, decreased rate of CO_2 increase) will occur as anticipated.[11]

U.S. policy makers are divided on the question of what, if any, steps the United States should take to reduce the emission of greenhouse gases.[12] EOS instruments will supply some of the needed scientific data on the effect of greenhouse gases on global warming (box B-2). Ultimately, researchers hope to advance climate models to the point where reliable predictions can be made about the magnitude of global warming and regional effects. Policymakers regard this information as essential to guide adaptation or mitigation efforts. In contrast, although the physical and chemical processes governing the depletion of ozone in the upper atmosphere have many uncertainties, the international community has agreed to reduce CFC emission in hopes of reducing ozone depletion. This difference in approach is clearly related to the availability of relatively inexpensive alternatives to CFCS. Pressure to act despite uncertainty was also influenced by predictions that various CFCS would reside in the stratosphere for 50 to 150 years after emission. In addition, aircraft and satellite observations of a growing ozone hole in the Antarctic fueled public pressure for action to stabilize ozone levels.

Steps to mitigate the effects of ozone depletion or global warming will require financial or other sacrifices. The relative cost of these mitigative efforts may be highest in developing nations. Building an international consensus on the appropriate steps to mitigate **ozone depletion and possible global warming will require a USGCRP program organized to answer the most important scientific questions. "Good policy" is most likely to flow from "good science."**

The rest of this section discusses three key instruments that were delayed or not funded:

[9] Solar ultraviolet radiation is the principal source of energy in the stratosphere and is responsible for many important photochemical processes. Ozone is concentrated in the stratosphere at altitudes between approximately 65,000 and 100,000 feet. The absorption of solar ultraviolet radiation by ozone is responsible for the increase in temperature with altitude that characterizes the stratosphere. The stratosphere is coupled to the lower atmosphere chemically (through photochemical processes), radiatively, and dynamically (various global circulation processes). See discussion and figure 4 in V. Ramanathan, Bruce R. Barkstrom, and Edwin Harrison, "Climate and the Earth's Radiation Budget," *Physics Today,* vol. 42, No. 5, May 1989, pp. 22-32.

[10] UARS is not a long-term monitoring satellite-its various instruments have expected lifetimes that range from approximately 14 months to 4 years. Currently, there is no planned follow-on to UARS. Although some of its instruments will fly on EOS platforms, a gap of several years in time-series of data is likely.

[11] Jerry D. Mahlman, "Understanding Climate Change," Draft Theme Paper prepared for Climate Research Needs Workshop, Mohonk Mountain House, Nov. 8, 1991.

[12] Policy Options for the United States are analyzed in U.S. Congress, Office of Technology Assessment, *Changing by Degrees: Steps to Reduce Greenhouse Gases,* OTA-O-482, (Washington, DC: U.S. Government Printing Office, February 1991).

Box B-2–The Greenhouse Effect

The Earth's atmosphere is composed of approximately 78 percent nitrogen, 21 percent oxygen, and a host of trace gases such as water vapor, carbon dioxide, and methane. Although these gases are nearly transparent to solar radiation, atmospheric water vapor, water in clouds, and other gases absorb about 20 percent of the incoming solar radiation, An additional 30 percent of the incoming solar radiation is scattered or reflected, especially by clouds, back into space. By contrast, the atmosphere is opaque to the less energetic infrared radiation emitted by the Earth's surface. About 90 percent of this heat energy given off the surface is absorbed by the clouds, water vapor, and trace gases such as CO_2, methane, and chlorofluorocarbons that are being increased by human activities.

Once absorbed in the atmosphere, the heat energy is reradiated, much of it back to the surface which can be further warmed, leading in turn to increased heat emission to the atmosphere and further absorption and reradiation to the surface. In this way, clouds, water vapor, and other trace gases have the effect of warming the surface (however, as noted above, clouds also cool the surface by reflecting incoming solar radiation back to space). In fact, the recycled energy reemitted from the atmosphere to the surface is nearly twice the energy reaching the surface from the Sun. It is this "greenhouse effect" that makes the Earth's climate different from the Moon. The analogy is not perfect, however, because it suggests that the atmosphere and the glass in a greenhouse lead to warming by the same mechanisms of trapping and reradiation. A greenhouse actually stays warm because the glass keeps the atmospheric moisture from escaping (which is why effective greenhouses are always humid), thereby reducing the cooling effect of evaporation. Despite the difference in how the mechanisms work, the term "greenhouse effect" has stuck, providing us with a reminder that allowing continued increases in the concentration of trace gases (and associated increases in the water vapor concentration) will eventually lead to future warming.

SOURCE: Quotation from "Systematic Comparison of Global Climate Models," Lawrence Livermore National Laboratory, *Energy and Technology Review,* **May-June 1990, p. 59.**

1. LASER ATMOSPHERIC WIND SOUNDER–LAWS

LAWS is a proposed Doppler laser radar[13] that would allow direct measurement of tropospheric winds with high resolution. As conceived by NASA, LAWS would provide wind speed and direction at different altitudes in the troposphere every 100 square kilometers to accuracies of 2 to 3 meters/second. Scientists would not only use this information in numerical weather prediction,[14] but also to understand a number of climate processes, including the transport of water vapor in the atmosphere and the heat, mass, and momentum coupling between the ocean and the atmosphere. In addition, if successful, LAWS would

[13] Also called lidar, for light radar. The Doppler shift is the change in laser frequency of the return, which 1S proportional to the scatterer's radial motion relative to the laser source. A familiar analog to this is the change in pitch that is heard as an ambulance siren or train whistle approaches and then recedes from a stationary observer.

In operation, a LAWS satellite would transmit a pulse of laser energy towards the Earth, some of which would be scattered back to the satellite by atmospheric clouds and aerosols. Scatterers in clouds and aerosols move with the local wind velocity. Therefore, wind velocities can be determined by analyzing the return signal's Doppler shift. The different altitudes at which the wind velocities are measured is determined by analyzing the round-trip travel time of the laser pulse.

[14] The input for numerical weather prediction models are maps of temperature, water vapor, and wind speeds and directions defined over a global network of model gridpoints. These maps, which may contain some 1,000,000 values, specify an ''initial state' of the atmosphere. Numerical weather prediction consists of using model equations to advance this initial set of data to a new set at a later time. Current systems are limited in their capabilities because they tack access to global wind fields.

It might be thought that wind fields could be derived from temperature fields, which can be roughly determined with current satellite systems. Although there are dynamical relations between temperature fields and wind fields, wind measurements have more information than do temperature measurements, especially for the smaller scales of motion that are of key importance for weather prediction. Source: Cecil Leith, Lawrence Livermore National Laboratory, private communication.

allow the determination of the distribution of aerosols and cirrus clouds, and the heights of cirrus and stratiform[15] clouds.

As initially proposed, LAWS was a large instrument with a mass of some 800 kilograms. It would fly on its own platform and its solar power supply would be required to supply some 2,200 watts of continuous power.[16] A space-based laser wind sounder requires large amounts of power because of the necessity to transmit high-power laser pulses and because candidate lasers convert only a small fraction of their input electrical energy into laser light.[17] The LAWS proposal called for a pulsed, frequency-stable CO_2 laser transmitter operating at the 9.11 micron line of the $C0_2$ laser system;[18] a 1.5 meter transmit/receive telescope; and a cooled detector. The laser transmitter would produce pulses with an energy of approximately 15 to 20 Joules per pulse, with a pulse repetition rate that could be varied between 1 and 10 pulses per second.

NASA established a 5-year lifetime requirement for LAWS. With laser repetition rates of 5 to 10 pulses per second, this is equivalent to requiring reliability over approximately 1 billion laser pulses. The high cost of LAWS (according to officials at GE Astro-Space Division, about $600 million in 1991 dollars) and uncertainty about the ability of a space-based CO_2 laser to maintain its pulse rate over 5 years were among the chief reasons that NASA chose not to fund LAWS in the restructured EOS program. Efforts to demonstrate that a CO_2 laser can deliver billion shot lifetimes led to the demonstration, by GE in the summer of 1992, of 100 million pulses from a sealed, laboratory system. GE Astro-Space officials believe that by adding a small, lightweight (less than 5 kg) gas refill system containing ten laser fills a LAWS space-based laser could achieve one billion pulses.

Research into laser alternatives for the CO_2 laser is proceeding in many locations, especially DOE national laboratories. In principle, solid-state lasers should be less prone to failure than high-power gas CO_2 lasers.[19] However, another potential advantage-the reduction in requirements for laser energy or the size of telescope optics—is less certain.[20] Development of space-based solid-state lasers for a LAWS mission will require the resolution of a number of technical issues.[21] Some of these are associated with

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15 Stratiform clouds, in particular marine stratocumulus, significantly affect the surface heat budget and may be important in regulating climate, Because marine stratocumulus are associated with regions of large-scale subsidence, they are typically not overlain by higher clouds, and hence would be observable by a space-based laser wind sounder. Source: Dr. Michael Hardesty, NOAA Wave Propagation Laboratory, Boulder, CO, private communication.

16 In an effort to reduce costs, a ''descoped'' LAWS has also been studied. This instrument would reduce the output power by a factor of 3-4 and reduce the telescope diameter to 0,75 meters. A LAWS science team meeting in Huntsville, AL, from Jan. 28-30, 1992, considered the science implications of building this instrument. They concluded that the descoped instrument could still measure tropospheric winds well enough to make important contributions to atmospheric general circulation models.

17 For example, the ''wallplug' efficiency of the baseline CO_2 laser is approximately 5 percent,

18 More precisely, this is a line in the $^{12}C^{18}O_2$ isotope laser, This line is chosen because the reduced abundance of this isotope in the atmosphere minimizes atmospheric attenuation.

19 For example, solid-state liners would avoid the difficulties of designing a long-lived gas handling system. They would also avoid the possibility of failure from electrode "poisoning' '—impurities introduced into the laser as a result of sputtering from the electric discharge electrodes. (However, based on the demonstration described above, GE researchers concluded that sputtering would not be a serious problem.)

20 The laser energy and size of telescope optics for a laser radar are related to the efficiency of the detection process, which may be measured by the signal-to-noise ratio (SNR) coming out of the detector, The leading candidate solid-state laser operates at a wavelength near 2 microns. A longstanding, and still unresolved, debate within the community of researchers developing LAWS is whether this shorter laser wavelength system would have overall superior performance compared to the proposed 9.1 micron CO_2 laser system.

21 These include the design of a system to provide the very accurate pointing of the narrow laser beam that is needed to ensure reception of the return signal. In addition, both the optics and the beam quality of LAWS would have to be near-perfect (i.e., near diffraction limited performance) because LAWS would use coherent detection to measure wind velocities. (Coherent detection mixes a stable frequency source with the return signal to generate a beat frequency that is proportional to the wind velocity,) CO_2 wind lidars with similar requirements for beam quality and optics quality have operated successfully on the ground for over a decade,

Several DOE national laboratories are also exploring the potential of noncoherent laser Doppler velocimetry, which would measure wind velocities without using coherent detection. Noncoherent methods have much lower requirements for pointing accuracy and beam quality. However, they may be less sensitive than coherent systems and they also have additionat requirements, for example, the necessity to measure the amplitude of the transmitted and received beam precisely.

the development of the requisite laser crystals, semiconductor array pumps, and coherent detectors; others are related to the pointing and stability of the shorter-wavelength system. Eye safety is also an issue of greater concern at the operating wavelengths of the solid state laser than it is with the CO_2 laser.

Currently, only the CO_2 system is far enough into development for consideration in early EOS flights. An effort to find international partners for this system is underway; GE officials also are exploring potential collaborations among NASA, DOE, NOAA, and DoD.

2. SYNTHETIC APERTURE RADAR-SAR

NASA originally proposed a SAR for the EOS program because of its unique ability to make high resolution global measurements of the Earth's surface (see box B-3), but decided not to fund it because of its probable high cost (over $1 billion in 1991 dollars). Operating at microwave frequencies, SAR radar returns are sensitive to the electrical and geometric properties of the Earth's surface, its cover, and its near subsurface. These data complement optical imagery and the combined data set may allow the study of such important Earth system processes as the global carbon cycle. Because SARS operate at microwave frequencies they are largely unaffected by clouds. This is particularly useful for monitoring the intensely clouded tropical and polar regions of the Earth. Operation during both day and night is also possible because SARS, like all radars, provide their own illumination in the form of radar energy.

SAR data could substantially improve the value of other EOS data. For example, researchers are particularly excited by the possibility of combining data from SAR about the physical properties of Earth's surface with data about chemical composition from HIRIS (see below). The combination would have the potential to date the ages of geomorphic surfaces and thus provide anew data set that would determine the rates of surface erosion and deposition.[22] A space-based SAR would also provide digital topographic data, vital for most hydrologic, geologic, and geophysical investigations. By using two antennas, SARS can be used in an interferometric mode to acquire global topographic data at resolutions on the order of 30 to 50 meters horizontal, 2 to 5 meters vertical.[23]

Synthetic aperture radar is a well understood technology with a long heritage of both civilian and military applications. The U.S. experience in flying space-based SARS for civilian applications began with the Seasat mission in 1978 and continued with SAR missions on Space Shuttle flights in 1981 and 1984 (Shuttle Imaging Radar-A & B). Currently, the Jet Propulsion Laboratory is preparing a third Shuttle imaging radar, SIR-C, for l-week flights in 1994-1996 (box B-4). SIR-C will include a German and Italian X-band SAR (and is therefore sometimes referred to as SIR-C/X-SAR); the combination of systems will form a multiangle, multifrequency, multipolarization radar (a "color" SAR) that will demonstrate the technologies necessary for EOS SAR.[24] Foreign experience in space-borne SARS includes the two SARS currently in orbit. These systems, built and operated by Japan and Europe, are free-flying systems designed for multiyear

[22] B.L. Isacks and Peter Moughinis-Mark, "Solid Earth Panel, " in *The Earth Observer*, vol. 4, No. 1, 1992, pp. 12-19. The *Earth Observer* is published by the EOS Project Science Office, Code 900, NASA Goddard Space Flight Center, Greenbelt, MD. As discussed below, budget cuts forced cancellation of HIRIS from the EOS program.

[23] Diane L Evans, Jet Propulsion Laboratory, personal communication, Apr. 20, 1992. The essence of the interferometric SAR technique is to transmit a radar pulse and usc the phase difference in signals received by two antennas, separated by a known distance, to infer ground elevations. The required distance between the separated antennas increases as the frequency is lowered. Thus, for example, L-band transmission would require locating receive antennas on two separate spacecraft. However, at Ka band, both antennas could be located on a single spacecraft (one located on a boom).

[24] The capability to vary radar incidence angle is necessary for measurements that require penetration to the Surface, for example, in mapping forest clear cuts. SIR-C, which is being developed by the Jet Propulsion Laboratory for NASA, is a two-frequency, multi-polarization SAR that can vary its angle of incidence from 15° to 55°. SIR-C/X-SAR is a joint project of NASA, the German Space Agency and the Italian Space Agency and will be the first spaceborne radar system simultaneously to acquire images at multiple wavelengths and polarizations. X-SAR, which Germany and Italy are providing, is a single polarization radar operating at X-band (3 cm wavelength). It is mounted on a bridge structure that is tilted mechanically to align the X-band beam with SIR-C's L-and C-band beams. SIR-C/X-SAR is scheduled to fly aboard the Space Shuttle on 3 missions in 1994-1996 and will acquire seasonal data on vegetation, snow, and soil moisture.

Box B-3-Synthetic Aperture Radar

Spaceborne radar systems may be classified in three general categories: imagers, altimeters, and scatterometers/spectrometers. Imaging radars are used to acquire high-resolution (few meters to tens of meters) large-scale images of the surface. They are used for the study of surface features such as geologic structures, ocean surface waves, polar ice cover, and land use patterns. A synthetic aperture radar is a special type of microwave radar-a "side-looking radar" (see figure B-2)-that achieves high resolution along the direction of motion of its airborne or spaceborne platform.

Radar resolution is usually defined as the minimum ground separation between two objects of equal reflectivity t hat will enable t hem to appear individually in a processed radar image. A sideways-looking radar has two resolutions: range resolution ("cross-track" resolution), which is perpendicular to the ground track, and azimuth resolution ("along-track") resolution, which is in the direction of motion. Range resolution is determined by the length of the radar pulse because objects at different ranges can only be distinguished if their radar returns do not overlap in time. Azimuthal resolution is determined in conventional radar systems by the width of t he ground strip that is illuminated by the radar, which is determined by the antenna beamwidth. Unlike conventional radar, the azimuthal resolution obtainable with a SAR is not determined by the size of antenna used in the measurement. A small antenna with a wide field-of-view can make high spatial resolution images by taking many closely spaced measurements.

Mathematically, an array of antennas is equivalent to a single moving antenna along the array line as long as the received signals are coherently recorded (i.e., phase information is retained) and then added. The SAR technique can be applied to spaceborne radar applications where the motion of t he spacecraft allows a particular object on Earth to be viewed from numerous locations along the orbital path. It can be shown that the best azimuthal resolution on t he ground using a synthesized array is equal to L/2, where L is the antenna length. This result is counter-intuitive because smaller antennas have higher resolution and because the ground resolution is independent of sensor altitude.

In his text on radar remote sensing, Charles Elachi notes that the fact that the resolution is independent of the distance between sensor and the area being imaged can be understood by noting that the farther the sensor is from the ground, the larger the footprint, and therefore the longer the synthetic array, This leads to a finer synthetic beam which exactly counterbalances the increase in distance.

The other surprise of synthetic aperture technique-finer resolution can be achieved with a smaller antenna-ca n be explained by noting t hat the smaller the antenna, t he larger the footprint and the synthetic array. This leads to a finer synthetic beam, and therefore, finer resolution, However, smaller antennas gather less energy than larger antennas. Therefore, for maximum signal-to-noise in the detected signal, a designer may choose the largest antenna that is consistent with the minimum required resolution and the volume constraints of the instrument package. (Another way to increase the signal-to-noise would be to increase the time the SAR dwells in scanning a particular scene; however, platform speed in low-Earth orbit (approximately 7 km/s) places practical limits on this method.)

The return radar echoes received by a SAR are spread over a time that is proportional to the distance between the SAR platform and various features in the target. In addition, interference between signals reflected from various parts oft he target will modify t he amplitudes and the phases of the echo signal pulses. Thus, synthetic aperture radar signals are unintelligible in their raw form; they must be processed electronically to produce a useful visual display. Uncompensated motion during aperture synthesis causes a blurring of the resultant SAR image. Techniques to deblurr these images using novel image processing software/parallel computer processing are being developed with the support of DOE and DoD.

(continued on next page)

Spaceborne synthetic aperture radars can achieve ground azimuthal resolutions that are hundreds or even thousands of times better than those from a real aperture system. (In practice, the azimuthal resolution is often made equal to the range resolution.) However, they require very fast on-board electronic processing and high-speed data links to the ground. Data are generated at **enormous rates in** SARs-for EOS SAR, 180 Mbps peak, 15 Mbps, average.

Satellite-based SARS have their **antenna, power, and data transmission requirements fixed by mission requirements such as spatial and temporal resolution and radar frequency.** For example, the frequency and altitude of a SAR drive antenna size requirements; the required signal-to-noise ratio is a important factor in determining transmitter power requirements; and the size and resolution of the area to be imaged dictate the required data rate. Power requirements scale as the cube of altitude; power-aperture products scale with the square of altitude.' Power, size, and weight requirements may be relaxed for aircraft-mounted SAR. However, compensating for a platform that vibrates and may be buffeted by winds and changing atmospheric conditions poses new challenges. In addition, aircraft-mounted SAR have the endurance limitations common to all aircraft-mounted instruments.

1 These factors are related by the "radar equation," which can be expressed in terms of the observed signal to noise ratio (SNR). The SNR is dependent on receiver performance. In addition it is proportional to the average transmitted power; the square of the antenna gain (proportional to area); the cube of the radar wavelength; the target radar "cross section," (a measure of target reflectivity); the cross-track resolution (which is related to the bandwidth of the radar processor and is therefore related to the noise); the inverse cube of the slant range to target; and the inverse of the spacecraft velocit y.

SOURCES: Briefings to OTA, Jet Propulsion Laboratory, January 1992; Charles Elachi, *Spaceborne* Radar Remote Sensing: *Applications and Techniques, (New* York, NY: The Institute of Electrical and Electronics Engineers, 19SS); and "Radar Images," in Sandia National Laboratory, *Sandia Technology: Engineering and Science Accomplishments, 1992,* pp. *32-33.*

operation. A similar free-flying Canadian SAR is scheduled for launch in 1995.[25]

All current and planned foreign space-based SARS operate in single-frequency, single-polarization mode. In contrast, the proposed EOS SAR, like SIR-C/X-SAR, would be capable of making multiangle, multifrequency, multipolarization measurements. These capabilities allow more information to be extracted from an analysis of radar backscatter and would give EOS SAR the potential to make global measurements of biomass, soil moisture, polar ice, and geology.[26] (Data from aircraft[27] and Shuttle-based experiments combined with advances in modeling of radar backscatter signals will be necessary to demonstrate that biomass and soil moisture measurements over vegetated land can, in fact, be made precisely enough to be useful to global change researchers.) Multifrequency, multipolarization SARS have been developed for aircraft experiments, but until recently they have been considered too challenging and expensive to incorporate in a free-flying spaceborne system.

In principle, EOS SAR could have been used to monitor and characterize forest growth. Atmospheric $C0_2$ from forests is a key unknown parameter in the

25 See ch. 4, Surface Remote Sensing and app. D for descriptions of existing SAR satellites.

26 Foreign SARs have more limited capabilities for global change research compared to the proposed EOS SAR. The European ERS- 1 operates in C-band (at 5.4 GHz). This frequency is especially suited for mapping sea ice and snow cover, but is not the preferred frequency for most EOS-class science missions. For example, studies of plant and soil moisture require lower frequency SARs because the lower frequency penetrates deeper into vegetation and soils. ERS-1 also does not have global coverage. The Japanese JERS-1 operates in L-band (at 1.3 GHz), and is preferred for more science missions. However, JERS- 1 has relatively poor signal-to-noise ratio. Its principal scientific objective is to study geology. The Canadian Radarsat will be a single frequency and polarization instrument operating in C-band (at 5.3 GHz), and will have a wide swath width, but its principal application will be to monitor polar ice in the northern latitudes. (The Russian Alrnaz, which de-orbited on Oct. 17, 1992, was a single polarization instrument that operated at a frequency near 3.1 GHz in the S-band.)

27 Airborne SARs include the Jet Propulsion Laboratory AIRSAR, a three-frequency polarimetric SAR that 1S providing prototype data for the Shuttle Imaging Radar-C (SIR-C) and the EOS SAR.

global carbon cycle.[28] EOS SAR would have complemented EOS MODIS, which will monitor CO_2 uptake in the oceans, by monitoring the extent of deforestation, the biomass of existing forests, and the successional stage of existing forests. Remote sensing studies of biomass in the tropical forest require a capability to sense both the forest canopy structure and the tree trunks underneath the canopy. Radar returns from the "C" band of EOS SAR would be sensitive to the canopy structure while the longer wavelength ''L' band would be able to penetrate the canopy and give information about tree height, biomass, and canopy architecture.[29]

The principal impediment in developing EOS SAR is its high cost, a direct result of the requirements for a high-power system with a large antenna. The European Space Agency's ERS-1 SAR cost nearly $1 billion[30] and the Japanese JERS-1 cost approximately $380 million. Early estimates of the cost of EOS SAR, including ground segment and launch costs, approached $1 billion.

Cost reductions are possible if ways can be found to lower power and size requirements. Program managers for EOS SAR generally believe that reducing power, mass, and size requirements will result from investment in what are, in effect, engineering programs[31]—scientists see no near-term technology 'breakthrough' that would change this conclusion. As noted earlier, program officials for both EOS SAR and LAWS raise concerns that government technology development efforts generally minimize funding for engineering and risk reduction programs and instead fund what is considered more basic science. Yet, investing in technology development may have significant payoff in more capable, lower cost technology.

Another option for EOS SAR would be to combine the data streams from a constellation of co-orbiting spacecraft, each carrying a single frequency SAR. The cost of each instrument might be reduced by using a standard instrument bus. A **more substantial opportunity for savings would come from international collaboration.** NASA and its sister agencies in Canada and Europe have begun informal discussions to explore the possibility of achieving the multifrequency capabilities proposed for EOS SAR through international partnerships. The European Space Agency (ESA) and Canada might provide C-band data (possibly with polarization diversity), the United States might provide L-band polarimetric data, and Germany might provide X-band data. To achieve the objectives of multitemporal observations and data continuity in the near term, the agencies have discussed develop-

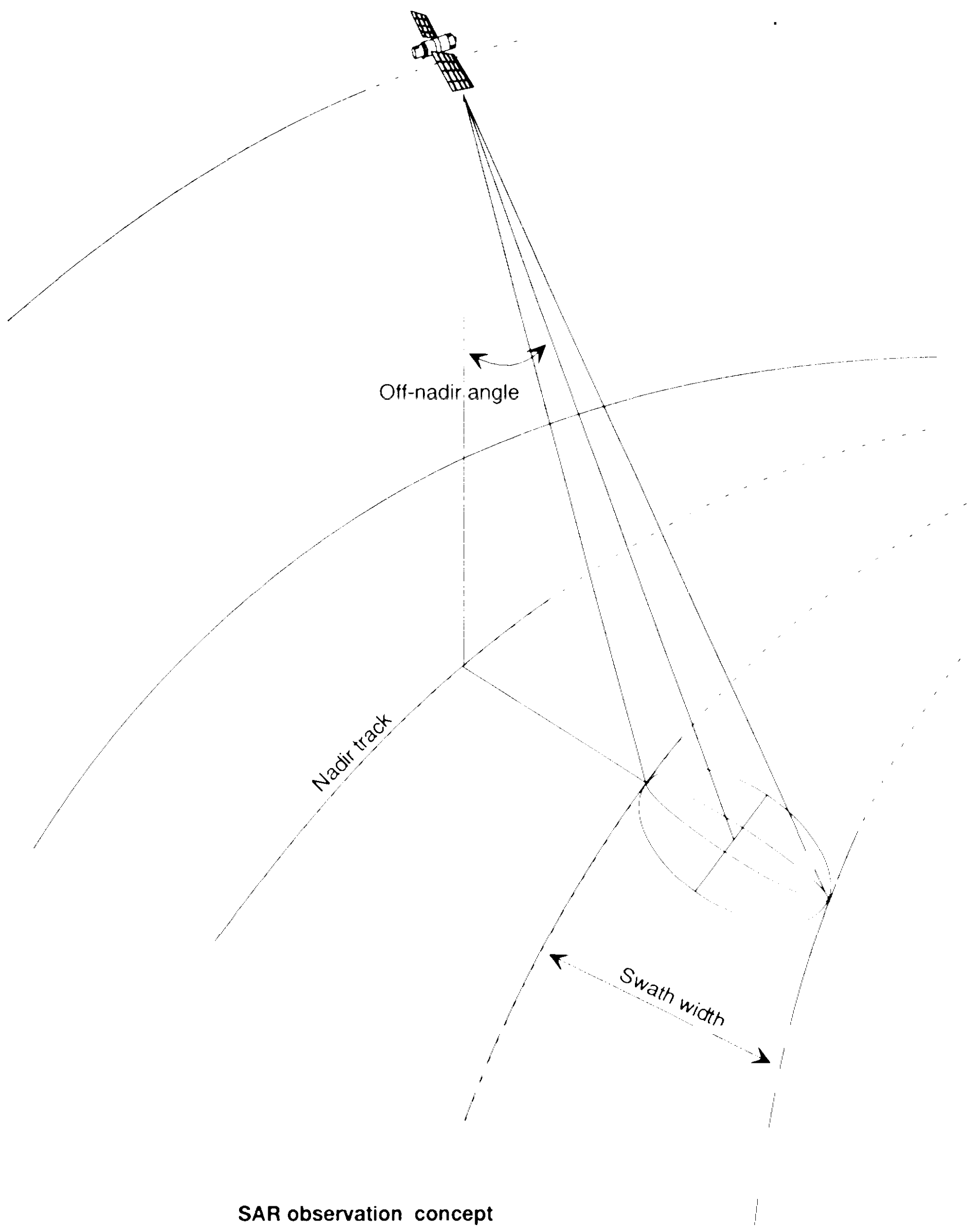
~ The global carbon cycle describes the movement of carbon from its sources and sinks in the ocean, atmosphere, and land (e.g., ice pack, tundra, jungles, marshes). For example, during the day, plants take carbon dioxide from the atmosphere and convert it into organic compounds such as carbohydrates by using solar energy and water (the process of ''photosynthesis' '). Plants emit CO_2 during respiration, when they use the energy stored in these compounds. The balance favors the net accumulation of carbon in trees, shrubs, herbs, and roots. When forests are cut, the effect on atmospheric CO_2 depends on how much carbon was stored (i.e., total biomass), what happens to the cut wood, and how the lands are managed (e.g., new vegetation will take up CO_2 unless the site is converted to a reservoir, highway, or other nonvegetative state. Source: U.S. Congress, Office of Technology Assessment, *Changing by Degrees: Steps To Reduce Greenhouse Gases,* OTA-O-482 (Washington DC: U.S. Government Printing Office, February 1991), pp. 201-203.

29 The SAR on the European ERS-1 has been limited in its capability to make soil moisture measurements, even though its frequency and incidence angle were specifically chosen for this application, because of the problem of differentiating between vegetation cover and ground moisture. EOS SAR would allow better separation of radar backscatter contributions from the Earth's surface and its ground cover. In principle, a multiangle, multifrequency, multipolarization SAR would allow soil moisture to be distinguished from canopy moisture or soil moisture to be distinguished from vegetation moisture. (Successful tests have occurred in aircraft experiments; however, EOS SAR would have to able to make similar measurements at an accuracy useful for global change.) The multiple frequency and polarization data of EOS SAR would be gathered simultaneously. This would allow researchers to monitor processes independent of diurnal or weather effects, for example, monitoring soil and canopy moisture, which will change from day to night or after a rainfall. Simultaneous measurements are also useful in monitoring ice in marginal ice zones.

30 This figure includes the cost to develop, build, and launch the satellite and to construct a network of ground receiving stations and facilities. In addition, the cost includes development of supporting instruments such as the Along-Track Scanning Radiometer. The cost to build a second radar satellite that would be similar to ERS- 1 and use the existing ground segment is approximately $500 million.

31 Although the component technologies for an EOS SAR are not new, the system possesses a number of unique requirements that stress design and add to cost. For example, special monolithic microwave integrated circuits (MMIC) with exceptionally linear response would be required. Similarly, specialized efforts would be needed to package SAR components in lighter weight and smaller structures. An attendee at OTA'S workshop on technologies for remote sensing noted that power efficient MMICs and lightweight antenna structures are examples of SAR-related technology that have suffered from lack of funding.

Figure B-2—SAR Observation Concept



SAR observation concept

Signals collected from different orbital positions are merged to create a narrow synthetic aperture beam.

SOURCE: Japanese Earth Resources Satellite-1 brochure, Japan Rcscurces Observation System Organization.

ment of a SIR-C/X-SAR flee-flyer in order to provide multiparameter SAR data prior to an EOS SAR mission. Discussions regarding exchange of science team members have been initiated in order to analyze these options further.

3. HIGH-RESOLUTION IMAGING SPECTROMETER–HIRIS

Since 1972, the Landsat series of satellites have imaged most of the Earth land surface at 80-meter and 30-meter resolution in several relatively broad visible and infrared spectral bands.[32] The reflectance characteristics of vegetation, soil, and various surface materials are sufficiently different that they can be distinguished by the relative strength of their reflectance in various combinations of these bands.

HIRIS was conceived as an ''imaging spectrometer' capable of making much more refined measurements of the Earths surface than Landsat by acquiring simultaneous images of the Earth in hundreds of contiguous narrow spectral bands. In principle, analysis of HIRIS data would allow direct identification of surface composition; for example, identifying specific minerals, specific types of trees or ground cover, pollutants in water, and vegetation under "stress."[33]

HIRIS would build on experience with the Airborne Visible and Infrared Imaging Spectrometer (AVIRIS), which became operational in 1988.[34] NASA's original HIRIS proposal envisioned an instrument that would collect images in 192 narrow spectral bands (approximately 0.01 microns wide) simultaneously in the 0.4 to 2.5 micron wavelength region. This range, from the visible to the near-infrared, contains nearly all of the spectral information that can be derived from passive sensors collecting reflected solar energy.

NASA chose HIRIS' spatial resolution to be *30* meters in part because of its use in vegetation research and geological mapping. For example, in forest ecosystems, successional changes in vegetation structure and function are linked to the size of gaps created by tree death, windfall, and other disturbances.[35] Thirty meters corresponds to the approximate size patch that develops in an Eastern hardwood forest when a tree is felled. It is also the approximate

Box B-4-Shuttle Imaging Radar

NASA has flown two models of a synthetic aperture radar on the Shuttle, the Shuttle imaging radar, SIR-A and SIR-B. Both instruments collected thousands of images of Earth's surface between +280 North and -280 South. SIR-C, an international effort that incorporates more advanced technology, is designed to fly on the Space Shuttle for l-week experiments in 1994, 1995, and 1996. The United States is providing a dual-frequency quad-polarization radar operating at L-band and C-band frequencies; Germany and Italy will supply an X-band imaging radar. The combined 3-frequency system (sometimes referred to as SIR-C/X-SAR) is the latest in a series of Shuttle imaging radars designed to demonstrate the technologies necessary for an EOS SAR. SIR-C/X-SAR will be functionally equivalent to EOS SAR and will be used to identify the optimum wavelengths, polarizations, and illumination geometry for use by EOS SAR. However, EOS SAR would not be attached to a shuttle and would require an independent power source from solar panels. It would also have more stringent volume and weight constraints. On the other hand, if launched on an expendable launcher, a free-flying SAR would not have to have the safety requirements of systems that are rated for flight with humans.

SOURCE: Jet Propulsion Laboratory: Briefing to OTA, 1992.

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32 Longer time-series of data is available from the series of Advanced Very High Resolution Radiometer (AVHRR) sensors that have been orbited on TIROS polar satellites. AVHRR provides multispectral imaging (2 visible channels; 3 infrared channels), but at much lower resolution (1 km and 4 km).

33 Alexander F. H. Goetz and Mark Herring, "The High Resolution Imaging Spectrometer (HIRIS) for EOS," *IEEE Transactions on Geoscience and Remote Sensing,* vol. 27, No. 2, March 1989, pp. 136-144. Plant leaf spectral reflectance has been shown to differ when plants are stressed by a variety of agents including dehydration and fungus attack. See Gregory A. Carter, ''Responses of Leaf Spectral Response to Plant Stress," *American Journal of Botany, 80(3): 239-243, 1993.*

34 A much more sensitive version of AVIRIS, HYDICE—hyperspectral digital imaging collection experiment-is being developed by the Naval Research Laboratory for aircraft flight in 1994. HYDICE will serve as a testbed for both the technologies that would enable HIRIS and for advanced aircraft-mounted sensors that could have military applications in land and ocean surveillance.

35 Goetz and Herring, op. cit., footnote 33, p 138.

resolution needed in some geological applications and is roughly the minimum resolution necessary to detect roads. Even higher resolutions may be desirable, but the combination of hyperspectral imaging, relatively high spatial resolution, and requirements for large dynamic range[36] already stresses many aspects of instrument design, especially data handling and transmission.

HIRIS was originally scheduled for flight on the second EOS-AM platform in 2003. Faced with the 1992 reductions in the proposed outlays for EOS, NASA deleted HIRIS because of its high probable cost (more than $500 million in 1991 dollars). Efforts to design a smaller, lighter, and therefore lower cost instrument are continuing. Proposals for a smaller HIRIS include reductions in required ground resolution (which reduces the size of instrument optics and peak data rates) and the use of active refrigeration to cool infrared focal plane arrays.[37] Establishing the cost of a smaller, lighter HIRIS is complicated by disputes over how much to budget to cover unanticipated costs associated with the introduction of advanced sensor technologies. Additional research is also required to establish the utility of HIRIS to support the highest priority missions of the restructured EOS program.[38]

| Platforms: Issues and Tradeoffs

Each remote sensing mission has unique requirements for spatial, spectral, radiometric, and temporal resolution (box 4-B). Numerous practical considerations are also present, including system development costs; the technical maturity of a particular design; and power, weight, volume, and data rate requirements. As a result, the selection of a "system architecture' for a remote sensing mission typically requires compromises and tradeoffs among both platforms and sensors. For example, some of the factors in determining system architecture for imaging of the land surface are the required geographical coverage, ground resolution, and sampling time-intervals. In turn, these affect platform altitude, the number of platforms, and a host of sensor design parameters.

SATELLITE V. NON-SATELLITE DATA COLLECTION

Remote sensing instrumentation can be placed in space on platforms that have a variety of orbital altitudes and inclinations. It can also be flown on endo-atmospheric platforms: aircraft (e.g., NASA's ER-2), balloons, and remotely piloted aircraft.[39] Finally, instruments can be sited at well-chosen locations on the Earth's surface.

Satellites play a central role in global change research because they facilitate global, synoptic, and repeatable measurements of many Earth systems (box B-l). Thus, for example, satellite-based measurements are ideal for monitoring changes in global biomass, land use patterns, the oceans and remote continental regions, and global processes that have large amounts of small-scale variability, such as weather.[40] However, satellite-based measurements also have a number of limitations that only complementary remote sensing programs can address.

Orbiting above the atmosphere, a satellite-based remote sensing system gathers information about the Earth by measuring emitted or reflected electromagnetic radiation. These signals are then manipulated into forms that can be used as input data for analysis and interpretation. However, the process that converts

36 Sensors capable of detecting signals that vary widely in intensity (large dynamic range) and characterizing signals freely (small quantization) are required to analyze scenes of widely varying reflectance and to characterize processes that may have only small differences in reflection.

37 NASA has specified Stirling cycle mechanical coolers for EOS for approved or potential instruments such as AIRS, SWIRLS, TES, HIRDLS, and SAFIRE. Only the Oxford Stirling cooler is space qualified (a Lockheed mechanical cooler maybe space qualified in the near fuhue----it is scheduled for flight in November 1994). Incorporation of mechanical coolers for EOS instruments wilt be possible only if current expectations for satisfactory cooling power, endurance, and vibration isolation are met.

38 HIRIS was initially proposed when geological applications had a higher priority. HIRIS investigators have been asked to show that space-based imaging spectrometry can, in fact, monitor portions of the carbon cycle. Source: Berrien Moore III and Jeff Dozier, ''Adapting the Earth Observing System to the Projected $8 Billion Budget: Recommendations from the EOS Investigators, " Oct. 14, 1992, unpublished document available from authors or from NASA Office of Space Science and Applications.

39 Some short-duration in-situ sampling of the atmosphere can also be accomplished using rockets.

40 Satellite-based measurements are not necessary to measure variables whose distribution is approximately uniform, for example, the atmospheric concentration of CO_2, which can be monitored at a few sites on the ground.

measurements into geophysical variables is often complex and data from nonsatellite measurements are necessary to reduce ambiguities in the analysis. Scientists also need to compare satellite data with surface-based or airborne measurements to verify that the satellite data are free of unforeseen instrument artifacts or unforeseen changes in instrument calibration. These comparisons are particularly important for long-term measurements and for measurements that seek to measure subtle changes. Satellite data must also be corrected to account for the attenuation and scattering of electromagnetic radiation as it passes through the Earth's atmosphere. In addition, corrections are necessary to account for the variations in signal that occur as a result of changes in satellite viewing angle.[41]

Another !imitation of sensors on satellites is their capability to make measurements in the lower atmosphere. They may also be unable to make the detailed measurements required for certain process studies. For example, an understanding of the kinetics and photochemistry that govern the formation of the Antarctic ozone hole (and the role of the Antarctic vortex) has only been possible with in-situ balloon and high-altitude aircraft experiments.[42] Ground and in-situ measurements also help ensure that unexpected phenomena are not inadvertently lost as a result of instrument or analysis errors .43 Satellite-borne sensors are also unable to measure climatological variables to the precision necessary for certain numerical weather and climate models, and their ability to determine temperature, moisture, and winds is inadequate for meteorologists interested in predicting, rather than just detecting, the formation of severe storms/hurricanes.

UNPILOTED AIR VEHICLES

Researchers interested in elucidating mechanisms for ozone depletion are particularly interested in obtaining a stable, controllable, long-endurance platform that could be instrumented to monitor conditions in the upper atmosphere at altitudes up to and above 25 km (approximately 82,000 feet). Scientific explorations of this region are currently hampered by the uncontrollability of balloons, the inadequate altitude capabilities and high operating costs of piloted aircraft, and the inadequate spatial and temporal resolution of satellite-borne instruments.

Several recent studies have concluded that unpiloted air vehicles (UAVS) are capable of carrying instruments that would provide unique and complementary data to the NASA's EOS program and to the DOE's groundbased Atmospheric Radiation Measurement program.[44] For example, high-altitude UAVS would allow detailed studies of the mechanisms involved in the formation, maintenance, and breakup of the Antarctic ozone hole. In turn, this information could provide researchers with the tools to *predictf the* onset of a similar hole in the Arctic. Positioning a UAV above a heavily instrumented site on the ground would also allow researchers to obtain accurate vertical profiles of radiation, water droplets, water vapor, ice particles, aerosols, and cloud structure-information that complements surface measurements and that is essential to test larger-scale models of atmospheric phenomena (UAVS would characterize processes occurring on a scale of General Circulation Model grid box, which is several tens of thousands of square kilometers) .45

41 See Jeff Dozier and Alan H. Strahler, "Ground Investigations in Support of Remote Sensing, " *Manual of Remote Sensing: Theory, Instruments, and Techniques* (Falls Church, VA: American Society of Phtogrammetry and Remote Sensing, 1983).

42 J.G. Anderson, D.W. Toohey, W.H. Brune, "Free Radicals Within the Antarctic Vortex: The Role of CFCS in Antarctic Ozone Loss,' *Science,* vol. *251,* Jan. 4, 1991, pp. 39-46.

43 The discovery of th, ''ozone hole'' above Antarctica provides an instructive example of the importance of ground-based observations (box A-3).

44 See Peter Banks et al., "Small Satellites and RPAs in Global-Change Research,'' JASON Study JSR-91-330 (McLean, VA: JASON Program Office, The MITRE Corp., July 13, 1992); U.S. Department of Energy, Office of Health and Environmental Research, *Atmospheric Radiation Measurement Unmanned Aerospace Vehicle and Satellite Program Plan,* March 1992 Draft (Washington, DC: Department of Energy, March 1992); and James G. Anderson and John S. Langford, eds., *Unmanned Aircraft: An Essential Component in Global Change Research,* version 1.0, June 1991, (available from authors). A popular article that discusses the potential role of UAVs in atmospheric research appears in Steven Ashley, ''Ozone Drone, " *Popular Science,* vol. 241, No. 1, July 1992, pp. 60-64.

45 Water vapor and clouds are the dominant regulators of radiative heating on the planet, and Uncertainty about the effect of clouds o climate is a source of fundamental uncertainty in climate prediction. Scientists have proposed UAVs for making some of these measurements.

Table B-l-Specifications of Airborne Measurement Platforms and Proposed Conventional Research Aircraft

Platform	Ceiling (km)	Range (km)	Endurance (hr)	Payload (kg)
McDonnell Douglas DC-8 (NASA)	12	9,600	12.0	13,700
Cessna Citation (NOAA, UND)	14	3,000	3.5-4.5	900
Gulfstream G-IV[a]	16+	7,400	10.0	9,500
General Dynamics WB-57	21	4,000	7.0	1,800
Lockheed ER-2 (NASA)	23	5,100	7.0	1,200

a Aircraft exists, but not currently equipped for atmospheric research.

SOURCE: Department of Energy, Office of Energy Research, Office of Health and Environmental Research, 1993.

UAVS are particularly suited towards making measurements at or near the tropopause, where the quality of remotely sensed data from both ground- and space-based platforms is poor. If developed, a long-endurance (multiple diurnal cycles) high-altitude UAV would effectively become a geostationary satellite at the tropopause. The tropopause is of particular interest because it marks the vertical limit of most clouds and storms.[46]

The instruments on UAVS can be changed or adjusted after each flight. UAVS are therefore potentially more responsive than satellite systems to new directions in research or to scientific surprises. Scientists have also proposed using UAVS as platforms for releasing dropsondes from high altitudes, a procedure that would provide targeted measurements of climate and chemistry variables at different altitudes in the atmosphere.

UAVS would be especially important in calibrating and interpreting satellite measurements. For example, scientists have proposed using UAVS to measure the angular distribution of solar and infrared radiation at tropopause altitudes, which is necessary to estimate flux and heating rates. Satellites are limited in their capabilities to make these measurements because they measure radiation from a limited number of angles. Currently, researchers using satellite data employ elaborate models to reconstruct angular distributions of radiation; limitations in the models remain a source of fundamental uncertainty in Earth radiation budget measurements. UAVS would both augment and complement satellite measurements of the effect of cloud cover on the net radiation balance.[47]

High-altitude UAVS have a smaller payload capability than currently available piloted aircraft (table B-1). However, they have several advantages that make them particularly attractive for climate research:

- UAVS under design should reach higher altitudes than existing piloted aircraft. For example, the ER-2 can reach the ozone layer at the poles, but it cannot reach the higher-altitude ozone layer in the mid- latitude and equatorial regions that would be accessible to a UAV.
- UAVS can be designed to have longer endurance than piloted aircraft.
- UAVS should have much lower operating costs than piloted aircraft. For example, estimates of direct and indirect costs for the piloted high-altitude ER-2 aircraft total some $15,000/hr of flight.[48] UAV studies predict savings of an order of magnitude or more.

46 In the tropics, the tropopause can reach altitudes of 18 km. Monitoring the tropopause with airborne platforms therefore requires vehicles capable of reaching an altitude of some 20 km. NASA's piloted ER-2 can reach this altitude, but it is restricted to flights of 6 hours.

A long duration UAV flying at or below the tropopause would facilitate measurements of two quantities of fundamental interest. One, the angular distribution of radiation, is necessary for measurements of the Earth's radiation budget, but is difficult to measure with satellites (see discussion below). The other, the flux divergence, can be related to the net heating that is occurring in a particular layer of the atmosphere. It is a fundamental parameter that appears in global circulation models of the Earth's atmosphere and climate.

47 Satellites fly above the Earth's atmosphere. A source of uncertainty in measurements of the effects Of clouds on the net radiation balance is the relationship between the ''top of the atmosphere' infrared and solar fluxes observed by satellite and the fluxes at the tropopause, which are the fundamental quantities of interest. See Peter Banks et al., op. cit., footnote 44, pp. 37-41.

48 Estimates from James G. Anderson, based in part on contract costs from Lockheed Corp.

Table B-2—Specifications of High-Altitude Unpiloted Aerospace Vehicles

Name	Status	Ceiling (km)	Range (km)	Endurance (hr)	Payload (kg)
Condor (Boeing)	Exists	23	29,000	30	900
Egrett II[a] (E systems)	Proposed	15	—	to be determined	900
Gnat 750-93L (General Atomic)	Proposed	20	—	75-85	150-550
HILINE	Proposed	13	—	18	45
Perseus-A (Aurora)	Under development	30	900-1,250	1-4	50-100
Perseus-B (Aurora)	Under development	20	13,000-19,500	36-72	50-200
Perseus-C (Aurora)	Proposed	15	3,000-12,000	15-65	50-200
Endosat-B[b] (Endosat, Inc.)	Proposed	20-30	50-100	months	100

[a] E-systems is the U.S. contractor for the German Egrett. Egrett II would be an unpiloted version of Egrett I, a high-altitude piloted vehicle that was used for border surveillance.

[b] Endosat would be powered by electrical energy generated by the rectification of a ground microwave source. Its range is limited to 50-100 km from the ground power source.

SOURCE: OTA; Aurora Flight Sciences Corp.; and Department of Energy, Office of Energy Research, Office of Health and Environmental Research, 1993.

- UAVS alleviate concerns about pilot safety on flights through polar or ocean regions.
- UAVS would be designed to fly at high altitudes at subsonic speeds. Supersonic high-altitude aircraft like the SR-71 (cruise altitude over 80,000 feet) are not suitable for many in-situ experiments because they disturb the atmosphere they are sampling (for example, the chemical species involved in ozone depletion).
- UAVS do not have the flight restrictions of piloted aircraft. For example, the ER-2 is restricted to daytime flight.
- The relatively low cost of UAVS compared to piloted aircraft should translate into more research aircraft and greater availability.

Table B-2 summarizes the characteristics of existing and proposed high-altitude UAVS. The altitude record for a propeller-driven UAV (67,028 feet or 20.4 km) is held by the Condor, a very large (200-foot wingspan, 20,000 pound) drone aircraft developed by Boeing for the DoD. The Condor has the range and payload capability to be useful to atmospheric scientists; furthermore, proposals exist to extend its operating ceiling to even higher altitudes (researchers would like UAVS to fly at altitudes of some 80,000 feet; in fact, NASA studies call for the design of aircraft capable of reaching 100,000 feet) .49 However, Condor would be an expensive vehicle to buy and adapt for scientific resea.rch.[50]

Aurora Flight Sciences, a company founded in 1989, is developing low-cost, lightweight UAVS specifically for the atmospheric science community (box B-5). Closest to development is Perseus-A, a high-altitude drone capable of carrying 50-100 kg payloads to altitudes above 25 km. The first two Perseus aircraft are scheduled for delivery to NASA in 1994 at a cost of approximately $1.5 -$1,7 million for each Vehicle.[51] NASA, foundations, and private investors have supplied funds to Aurora for this work.

Both NASA and DOE (in its ARM program) plan to use UAVS for key experiments. In addition, the development of sensors for UAVS relates closely to the development of sensors appropriate for small satellites. Despite the potential of UAVs to enable measure-

49 "Subsonic Airplane fo, High Altitude Research," NASA Tech Briefs, ARC-12822, Ames Research Center, Moffett Field, CA. The difficulty in designing a high-altitude subsonic aircraft is directly related to the challenge of designing propulsion systems, wing structures with sufficient lift, and heat transfer systems appropriate for operation in the tenuous reaches of the upper atmosphere. The density of air falls off rapidly with increasing altitude (an exponential decrease).

50 Unofficial industry estimates provided to OTA suggest that restoring one Condor could cost $20 million and yearly mainentance costs would be severat million dollars or more.

51 NASA may exercise an option for a third vehicle, which might lower unit aircraft costs. Aurora Flight Sciences Corp. is supplying an existing ground station for use with Perseus A. Development of Perseus B is also proceeding at Aurora. It is being funded with internal monies and several small grants, including one from the Nationat Science Foundation.

Box B-5 The Perseus Unpiloted Aerospace Vehicle

Perseus A is designed to carry payloads of about 50 kg to altitudes of 30 km in support of stratospheric research. Perseus A will carry liquid oxygen to support combustion because air densities at 30 km are only some 2 percent those of sea level.

Perseus B would trade altitude for payload mass and flight duration. It would also replace the closed-cycle engine design of Perseus A with a two-stage turbocharged engine. This more complicated engine avoids the payload penalty incurred by carrying on-board oxidant and is the key to long endurance.

Perseus C would be designed for mid-latitude meteorological research and be capable of carrying 100 kg payloads to altitudes of 12-15 km.

SOURCE: Perseus Payload User's Guide, Aurora Flight Sciences Corp., 1992.

ments crucial to the global change research program, congressional support for civilian UAV development, and associated instrumentation, has been meager and may be inadequate to provide a robust UAV capability.[52] If it wishes to encourage innovation in global **change research, Congress may wish to increase funding for the development of UAVS specifically designed for** USGCRP missions. Because UAVS could be highly cost effective, moderate funding increases of only a few million dollars per year could ultimately lead to a major increase in UAV availability for research.

THE ROLE OF SMALL SATELLITES IN EARTH OBSERVING PROGRAMS

"Small" satellites have been defined as costing $100 million **or less including spacecraft, instruments,** launch, and operations. As noted in ch. 5, NASA, DOE and ARPA are examining small satellite systems for three roles in the U.S. Global Change Research Prograrn:[53] 1) to address gaps in long-term monitoring needs prior to the launch of EOS missions, 2) to provide essential information to support process studies prior to, and complementary with, the restructured EOS, and 3) to allow for innovative experiments to demonstrate techniques that greatly improve the ability to monitor key variables or improve/speed up the process studies.[54]

Small satellites have three advantages as complements to larger systems, First, they are characterized by relatively low cost compared to larger satellites.[55] This facilitates 'risk taking' and encourages technical innovation. Small satellite proponents see this advantage as the key to enabling rapid, affordable augmentation and modernization of larger satellites. Second, small satellite missions can be developed in only a few years or less. Typically, development of a small satellite avoids the potential problems associated with managing the integration of multiple instruments on a single platform. Shortening the time to launch would add resilience to the satellite portion of the global change research program, large parts of which are frozen in development some 10 years before flight. Third, flying only a small number of instruments per satellite allows orbits to be optimized for a particular set of measurements.[56]

52 For example, although the FY 93 USGCRP report to Congress gave strong support for a $10 million dollar new start by the DOE to develop a UAV program, tight budgets prevented its implementation. For further information, see *Our Changing Planet: The FY 1993 U.S. Global Change Research Program* (Washington DC: National Science Foundation, 1992), p. 71.

53 See Committee on Earth and Environmental Sciences (CEES) of the Federal Coordinating Council for Science, Engineering, and Technology, *Report of the Small Climate Satellites Workshop* (Washington, DC: Office of Science and Technology Policy, May 1992).

54 *Report of the Small Climate Satellites Workshop,* pp. 20-21. In addition to these missions, researchers at the Goddard Institute for Space Studies have proposed using small satellites for long-term (decadal-scale) monitoring in a program that would complement EOS.

55 They also weigh less and do not require as expensive a launcher. However, launch costs are small compared to other EOS costs. Multi-instrument EOS AM and PM satellites, Landsat 6, Landsat 7, and proposed EOS facility instruments-LAWS, SAR, and HIRIS—require a launcher in the Atlas 2AS-class. Launch costs with an Atlas 2AS may be some $130 million, but this is 20 percent or less of total system costs (which also includes ground segment costs).

56 However, some missions require nearly simultaneous measurements by instruments that cannot be packaged on a single satellite. In this case, a larger platform carrying severat instruments may be desirable. Another option would be to attempt to fly small satellites in close formation.

57 For a more detailed discussion of this subject see V. Ramanathan, Bruce R. Barkstrom, and Edwin Harrison, ' 'Climate arid the Earth's Radiation Budget, " *Physics Today,* vol. 42, No. 5, May 1989, pp. 22-32.

Box B-6—The Effect of Clouds on the Earth's Radiation Budget

Clouds regulate the radiative heating of the planet. They cool the Earth by reflecting a large part of the incoming solar radiation, increasing the Earth's reflectance by approximately a factor of 2. They also warm the Earth because they absorb some of the long-wavelength infrared radiation (emitted by the warmer Earth below) as well as emit radiation back to space at the colder temperatures of the cloud tops. High clouds tend to cool the Earth while low clouds tend to warm it.

Measurements made with space-based detectors show that the heating and cooling effects of clouds are comparable in magnitude and are about a factor of ten larger than that expected for a doubling of CO_2. **A key uncertainty in predictions of future climates is how cloud heating and cooling might change in future atmospheres that are likely to contain greater abundances of CO_2 and other trace greenhouse gases.**

SOURCE: V. Ramanathan et al., "Cloud-Radiative Forcing and Climate: Results from the Earth Radiation Budget Experiment" and John Vitko, Jr., Sandia National Laboratory, private communication, Jan. 25, 1993.

A SMALL SATELLITE "GA P-FILLER' '-CLOUDS AND THE EARTH'S RADIATION BUDGET[57]

The effects of human activities on the planetary energy balance are a principal focus of climate change research. The Earth's energy balance or ''radiation budget' consists of incident sunlight, reflected sunlight (e.g., from the tops of clouds), and radiation emitted back to space, primarily from the Earth's surface and atmosphere. The emitted radiation falls predominantly in the infrared and far-infrared portion of the electromagnetic spectrum, The radiation budget is directly related to climate because the balance between the absorbed solar energy and the emitted energy determines the long-term average global temperature. In addition, the temporal and spatial variations of the radiation balance are linked to the global circulation patterns of the atmosphere and the oceans.[58]

Lack of knowledge concerning how changes in cloud type and cover[59] affect the radiation budget is a principal source of uncertainty in 1) predicting climate changes associated with anthropogenic increases in greenhouse gases; and 2) understanding past and future climate changes caused by variations in solar output or in the orbital characteristics of the Earth[60].

Scientists have monitored the Earth's radiation budget with spaceborne instrumentation since the early 1960s.[61] The most precise measurements of the radiation balance and the effects of clouds (box B-6) were made with sensors that were part of the Earth Radiation Budget Experiment (ERBE) (box B-7). **long-term measurements of the radiation budget and related data are necessary to distinguish between anthropogenic and naturally occurring variations in Earth's climate. Continuing measurements of Earth's radiation budget, and the effect of clouds and aerosols, are necessary to establish a baseline that might guide future policy decisions.**

58 Many coupled ocean.atmosphere-land interactions influence the radiation budget. For example, the intensity of radiation emitted from the land surface varies with surface temperature. However, surface temperature depends on such factors as the amount of incoming solar radiation, which is affected by atmospheric absorption and scattering (which can be altered by human induced greenhouse gas changes or by natural events such as volcanic eruptions), and the effects of clouds. Surface temperature is also affected by surface moisture (because the surface cools by evaporation), which in turn is affected by surface composition and the presence of surface vegetation. Cloud formation and distribution depend on a host of coupled ocean-atmosphere-land processes.

59 These changes include the distribution and fractional cover over land and ocean, and changes in cloud altitude, latitude, and reflectivity. The optical reflectivity of clouds is itself a sensitive function of the detailed internal structure of the cloud, for example, the size and distribution of water droplets and ice crystals.

60 Solar output has been measured since 1978 and has fluctuated by approximately 0.1 percent. As noted earlier, the Earth absorbs approximately 240 watts/m^2 of solar energy. Based on correlation of measured irradiance changes with visible features on the Sun, scientists suspect that solar irradiance may vary by several tenths of a watt per century. Changes of Earth's orbit (e.g., its eccentricity or the inclination of its spin axis) occur on time scales ranging from approximately 20,000 to 100,000 years. Source: Johan Benson, ' 'Face to Face, Interview with James Hansen, *Aerospace America,* April 1993, p.6.

61 Andrew Careton, *Satellite Remote Sensing in Climatology* (Boca Raton, FL: CRC Press), pp. 206-209,

NASA plans to continue radiation budget measurements as part of EOS by flying radiation budget sensors on the U.S./Japan[62] satellite and on the AM-1 platform (the CERES instrument, a follow-on to ERBS). TRMM and AM-1 are scheduled for launch in 1997 and 1998, respectively. NASA plans related flights of SAGE,[63] the stratospheric aerosol and gas experiment, as part of EOS. NASA officials acknowledge the desirability of flying CERES and SAGE missions before EOS flights in the late 1990s, both to assure data continuity and to have instruments in place before the next occurrence of El Nino-type events in 1995-1997 (see box B-8).[64] Researchers would also like to have instruments in place to monitor climate-changing surprises such as the eruption of Mt. Pinatubo. However, NASA has not identified sources of funding for these missions.

Researchers attending OTA'S workshop on the future of remote sensing technology stressed that, to be useful, radiation budget sensor systems must have very high-quality calibration, long-term stability, and fully developed data processing systems. Similar concerns govern the ACRIM mission (see box B-9). Measurements taken on successive satellites must also overlap for a sufficient time period to allow the two systems to be intercalibrated.

Sensor requirements of fine calibration and long-term stability can be understood intuitively by observing that the radiation balance is the *difference* between large energy inputs and outputs. Therefore, relatively small measurement or calibration errors in incoming or outgoing radiation will lead to errors in the energy balance that would mask evidence of an actual change. Similarly, changes in the way raw data are converted to radiation intensities could mask small changes in the radiation balance.[65]

A small satellite that would include the CERES instrument is among a number of small satellites being

62 TRMM, the tropical rainfall measuring mission, will combine a NASA-supplied spacecraft with a Japanese launch vehicle. The payload for TRMM will be supplied jointly.

63 SAGE I flew from February 1979 to November 1981. SAGE II has been flying on the ERBS satellite since October 1984, a period well beyond the instrument design life. Flights of SAGE III before the year 2000 were recommended by the Payload Advisory Panel of the EOS Investigators' Working Group in October 1992 because 'SAGE has demonstrated that it can monitor consistently and overlong term several parameters that are crucial to global change: a. vertical profiles of ozone, b. stratospheric and tropospheric aerosol loading, and c. water vapor in the upper troposphere and lower stratosphere. The SAGE ozone measurements are now a key component of the present monitoring of the changing stratospheric ozone; the aerosol measurements are crucial for assessing the variability of solar forcing to the climate system consequent to the sporadic and highly variable volcanic aerosols. " See Berrien Moore III and Jeff Dozier, "Adapting the Earth Observing System to the Projected $8 Billion Budget: Recommendations from the EOS Investigators," Oct. 14, 1992, unpublished document available from authors or from NASA Office of Space Science and Applications, pp. 23-25.

1$1 Earlier flights of SAGE III on a ' 'mission of opportunity" is advocated by EOS' Payload Panel Advisory Group. One such flight would be on a planned NOAA weather satellite that could accommodate SAGE without necessitating expensive modification of the bus or causing significant changes in the planned instrument package. NOAA's 'AM" TIROS series is a suitable candidate (it has a space where the SBW sensor is placed for "PM' flights); a 1997 launch might be possible if funding is identified. However, even if this gap-falling mission were launched, sampling of diurnal variations would still be lacking because NOAA weather satellites fly in polar, sun-synchronous orbits. To fill the potential gap in SAGE data and to supply data from inclined orbits, scientists have proposed flight of SAGE II on a planned 1995 Russian launch. As of June 1993, NASA officials had not identified funding for either of these options.

65 Deriving radiation budget &_from satellite-based instrument measurements is an extremely complex process that requires sophisticated models and computer programs. The steps involved in processing radiation data include:

- Convert instrument counts to radiant energy at detector.
- Unfilter that signal to the front end of the instrument (i.e., put back what was lost in the instrument's optical path). This correction is scene dependent.
- Convert to radiance at the top of the atmosphere.
- Convert radiance to flux using angular-directional models.

Robert Cess, "Science Context of Small Global Change Satellites or Perspectives From One Who Would Like To Have Satellite Radiometric Data Before He Retires or Expires, '' in Paul V. Dreseler and Jack D. Fellows, co-chairman, *Collected Viewgraphs: A Supplement to the Report of the Small Satellites Workshop, (Washington* D.C.: Committee on Earth and Environmental Sciences, June 1992).

Box B-7–Earth Radiation Budget Experiment (ERBE)

ERBE (Earth Radiation Budget Experiment) is a NASA research instrument that consists of two parts. The first is a relatively wide fixed field-of-view instrument with four Earth-viewing radiometers and a Sun-viewing radiometer equipped with shutters. The Earth-viewing radiometers monitor outgoing Earth radiation in two bands: 0.2 to 5 microns (short-wave infrared) and 0,2 to 50 microns (broadband total). The second part of ERBE is a narrow field-of-view (instantaneous field of view of approximately 3°) three-channel (0.2 to 50,0.2 to 5.0, and 5.0 to 50 micron) instrument that can be scanned. ERBE data allow an analysis of monthly and seasonal variations of the radiation balance at regional scales. They also allow an analysis of the effect of clouds on the radiation budget. As noted in the text, analysis of ERBE data to date has shown that the net effect of clouds is a small cooling of the Earth. scientists are still unsure how the planetary energy balance will be affected by clouds in future atmospheres that are likely to contain higher concentrations of greenhouse gases such as $C0_2$.

To monitor the Earth's radiation budget properly, daily global data from two polar orbits (A.M. and P. M.) and a mid-latitude inclined orbit of 50-60 degrees are required. ERBE sensors flew on the Earth Radiation Budget Satellite (ERBS), which was launched by the Space Shuttle into a low-inclination, non-sun-synchronous orbit and the NOAA 9 and NOAA 10 operational weather satellites, which are in sun-synchronous polar orbits. These were launched in December 1984 and July 1986, respectively. Five years of data were collected before the last ERBE scanner failed in 1990.[1]

1 Non-scanner measurements are continuing on the NOAA-9 and NOAA-10 and data are continuing to be archived. However, the ability to characterize the scene covered by ERBS, which is crucial in radiation budget measurements, is limited because the non-scanners have a relatively wide field-of-view. As a result, the data have limited utility compared to the data that was being provided by the ERBS narrow field-of-view scanner.

SOURCE: National Aeronautics and Space Administration and Office of Technology Assessment, 1993,

considered for joint missions among NASA, DOE,[66] and DoD (through ARPA). (However, as noted earlier, budget constraints and other difficulties have delayed implementation of these proposals.) NASA officials interviewed by OTA supported efforts by DOE and DoD for collaboration because interagency cooperation may be the key to ensuring the long-term support that is necessary for multidecadal missions such as ERBS. In addition, harnessing the expertise resident in DOE laboratories could accelerate the development of technologies that promise to reduce mission costs.

CLIMSAT: A SMALL SATELLITE COMPLEMENT TO EOS

The rationale for launching a series of small environmental monitoring satellite*Climsat-was discussed in ch. 5. The several decade record of high-quality data on CO_2 abundance in the atmosphere is a prototype for the kind of measurements that Climsat would perform (figure B-3). CO_2 change is a key climate forcing variable. In addition, the historical CO_2 record provides an important constraint on analyses of the carbon cycle and directs researchers to the kind of detailed measurements needed to understand the observed CO_2 change.[67] In the same way, Climsat's long-term monitoring of other global forcings and feedbacks would help bound the thermal energy cycle and direct researchers toward detailed measurements of climate processes (some of these measurements would be made in the EOS program).

66 Research groups in the DOE have proposed to build and launch, by 1995, one or more small spacecraft equipped with radiation budget instruments similar to those now flying on ERBS, or with what they believe would be an improved sensor. The improved sensor, which would be designed by DOE, promises better capability in analyzing the spectral content of the received signals. DOE researchers believe their sensor would therefore allow a better understanding of climate forcing from, for example, CO_2 and water vapor. However, the importance of stability in instrument calibration and data analysis argue for a cautious approach when considering major departures from previous ERBE sensors.

67 James Hansen, NASA Goddard Institute for Space Studies, personal communication, 1993.

Box B-8-The Linkage Among Earth's Systems: El Nino and the Southern Oscillation

Coastal Peru is arid enough so that sun-baked mud is often used to build houses. In the neighboring ocean, intense upwelling pumps nutrients tot he surface to create one of t he world's richest fisheries. In late 1982 the nutrient pump shutdown, eliminating the local fishery. And the rains began: some normally arid zones received as muchas3m[118 inches] of rain within a 6 month period. Mud houses dissolved, and much of the transportation infrastructure washed away. Almost 1,000 years ago, a similar climatic disaster destroyed a prosperous agricultural civilization rivaling the Incas.

Peru was not alone: the impact of the strange climatic events of 1982-83 was global. In Indonesia, vast areas of rainforest were destroyed in fires spawned by a devastating drought. Australia experienced the worst drought in its recorded history: firestorms incinerated whole towns, livestock herds had to be destroyed, and production of cotton, wheat, and rice was sharply reduced. In Brazil, an exceptionally poor rainy season distressed the impoverished Nordeste region, while southern Brazil and northern Argentina were hit with destructive flooding. Throughout southern Asia, poor monsoon rains in 1982 reduced crop yields and slowed economic growth. China saw drought over the northern part of the country and unusual winter floods in the south, leading to major losses in the winter wheat crop. . . Severe winter storms rearranged the beaches of California; spring floods covered the streets of Salt Lake City. . .

The above paragraphs describe events that occurred as a result of an irregularly recurring pattern known as ENSO. The acronym combines its oceanographic manifestation in the eastern tropical Pacific, El Nino, with its global atmospheric component, the Southern Oscillation. ENSO is an irregular cycle with extremes of variable amplitude recurring every 2 to 7 years. The 1982-83 events are an instance of its warm phase. Events of 1988, including catastrophic flooding of Bangladesh, demonstrate the impact of t he cold phase. Historically El Nino was the name given to the marked warming of coastal waters off Ecuador and Peru. It is now understood that during the ENSO warm phase the warming covers the equatorial Pacific from South America to the dateline, fully one-quarter of the circumference of the Earth (plate 8).

SOURCE: Mark A. Cane, ***Geophysics Report: El Nino and the Southern Oscillation (ENSO),*** **Larnont-Ooherty Earth Observatory, Columbia University,**

Although Climsat is designed for long-term measurements, it would also address short-term issues.[68] These include:

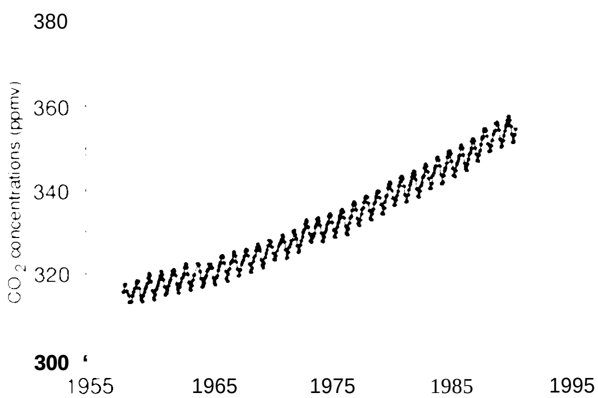
- Assessment of climate forcing resulting from ozone change versus forcing that results from changes in CFC concentrations.
- Assessment of climate forcing resulting from anthropogenic tropospheric aerosol change versus CO_2 change.
- Short-term tests of climate models/understanding (e.g., effects of volcanic aerosols).

Each Climsat satellite would carry three instruments (box B-10). Versions of two of these instruments, SAGE ILI[69] (Stratospheric Gas and Aerosol Experiment) and EOSP (Earth Observing Seaming Polarimeter), are part of the current plans for EOS. However, first launches of these instruments may not occur until

[68] These issues are among those discussed in the Supplementary Report to the Intergovernmental Panel on Climate Change @CC) Scientific Assessment (an update of the 1990 report). The IPCC supplementary report concludes that stratospheric ozone depletion may be offsetting much of the greenhouse warming caused by CFCS. In addition, cooling by tropospheric aerosols from sulfur emissions may have offset a significant part of the greenhouse warming in the northern hemisphere during the past several decades.

[69] SAGE III is an improved version of SAGE II, now in orbit. It should increase the accuracy of aerosol, ozone, and water vapor measurements. It should also permit extensions of these measurements deeper into the troposphere.

Figure B-3-Carbon Dioxide Concentrations in the Atmosphere



The Mauna Loa atmospheric CO_2 measurements constitute the longest continuous record of atmospheric CO_2 concentrations available in the world.

SOURCE: See Charles D. Keeling and Timothy P. Whorf, "Atmospheric CO_2—Mauna Loa," in *Trends '91: A compendium of Data on Global Change*, Carbon dioxide Information Analysis Center, Publication ORNL/CDIAC-46 (Oak Ridge National Laboratory, Oak Ridge, TN, December 1991), pp. 12-14.

the year 2000 or later under the current EOS schedule.[70] The Climsat mission would have one satellite in sun-synchronous polar orbit and the other in an inclined orbit that drifts in diurnal phase. Having SAGE III on both these satellites would provide global coverage and allow researchers to sample diurnal varaitions.[71] EOS might duplicate this coverage for SAGE III, assuming SAGE III flies to inclined orbit on a Pegasus in 2000 and to polar orbit on a multi-instrument platform around the year 2002. EOSP is currently scheduled for inclusion only on the second AM platform in (approximately) 2003.[72]

SAGE III was recommended for inclusion in EOS principally because of its capability to make high-accuracy measurements of the vertical distribution of ozone and stratospheric aerosols. These measurements will be made in a geometry that allows SAGE III to observe the sun or moon through the limb of the Earth's atmosphere. A dramatic example of the impact of aerosols on Earth's climate is the apparent global cooling effect of the June 1991 eruption of Mt. Pinatubo in the Philippines.[73]

EOSP measures the radiance and polarization of sunlight reflected by the Earth in 12 spectral bands from the near ultraviolet to the near infrared. Among the principal objectives of EOSP are the global measurement and characterization of tropospheric aerosols, surface reflectance, and cloud properties (e.g., cloud top height and cloud particle phase and

70 Earlier flights of SAGE III on a ''flight of opportunity '' is advocated by EOS' Payload Panel Advisory Group. One such flight could be on a planned NOAA weather satellite that could accommodate SAGE without necessitating expensive modification of the bus or causing significant changes in the planned instrument package. NOAA's ' 'AM' TIROS series is a suitable candidate; a 1997 launch might be possible if funding is available, However, even if this gap-filling mission were launched, sampling of diurnal variations would still be lacking because NOAA weather satellites fly in polar, sun-synchronous orbits.

71 A Climsat in a sun-synchronous near-polar orbit would provide a fixed diurnal reference. The second satellite would be placed into in a processing orbit inclined 50-60[72] to the equator. It would provide a statistical sample of diurnal variations at latitudes with significant diurnal change.

72 An EOSP predecessor instruments that was launched on a mission to Venus allowed scientists to derive valuable data on cloud and haze characteristics and structure. However, the capability of EOSP to make similar measurements over Earth is complicated by Earth's more varied surface reflectivity and polarization characteristics, particularly over vegetated-covered land. As part of its plan to adapt EOS to funding of $8 billion for 1991-2000, instead of$11 billion, NASA accepted the recommendation of its advisory group to delay EOSP until the second AM platform in 2003.

Climsat supporters at the Goddard Institute for Space Studies argued against the delay in EOSP. Their reasons for believing EOSP could make the required aerosol measurements were based on both experimental and theoretical studies. These studies are detailed in J. Hansen, W. Rossow, and I. Fung, "Long-Term Monitoring of Global Climate Forcings and Feedbacks," Proceedings of a Workshop held at NASA Goddard Institute for Space Studies, Feb. 3-4, 1992, pp. 4&47.

73 The plume from the eruption deposited great quantities of gases (e.g., SO_2) and ash into the stratosphere where they produced optically significant quantities of aerosols that are expected to remain for several years. (Photochemical reactions convert the SO_2 to sulfuric acid, H_2SO_4, which subsequently condenses to form a mist of sulfuric acid solution droplets. Sulfate aerosol is a mixture of sulfuric acid and water). Because of their small size, these aerosols are more effective at reflecting shortwave solar radiation than they are at attenuating the longer wavelength thermal radiation emitted by the Earth. Thus, the aerosols alter the Earth's radiation balance by reflecting more of sun's energy back to space while permitting the Earth to COOI radiatively at approximately the same rate as before the eruption. The result is a net loss of energy for the Earth atmosphere system, or a cooling of the atmosphere and surface. See P. Minnis et. al., ''Radiative Climate Forcing by the Mount Pinatubo Eruption, " *Science*, vol. 259, No. 5100, Mar. 5, 1993, pp. 1411-1415.

Box B-9-Why Remote Sensing Places Particular Demands on Instrument Calibration and Stability

Much of global change research consists of establishing long-term records that will allow anthropogenic changes to be distinguished against a background of naturally occurring fluctuations. Therefore, measurements must be finely calibrated, instruments must have long-term stability, and data reduction and analysis algorithms must be well understood. Measurements of the Earth's radiation budget illustrate these requirements. Another example of the need for finely calibrated data in global change research is provided by the ACRIM (active cavity radiometer irradiance monitor) instrument to monitor long-term changes in the total solar output. This instrument is currently not on the EOS flight manifest, but NASA officials have stated their desire to fly ACRIM on a "flight of opportunity."

The interaction of the Earth and its atmosphere with the total optical solar radiation from the sun determines weather and climate. Even small variations in the total solar output would have profound effects on both weather and climate if they persisted. Scientific evidence exists for past climate changes, including cyclic changes ranging in period from the approximate 11-year solar activity cycle to many millions of years. Variations in solar output are suspected as the cause of some cycles, particularly short-term ones.

Acquiring an experimental database on solar variability is a necessary first step in testing hypotheses about how solar variability might affect climate. It is also necessary if researchers are to distinguish variations in solar output from other climate "forcings" such as changes in concentration and vertical distribution of infrared trapping "greenhouse" gases, aerosols, and clouds. Previous ACRIM measurements, beginning with the "Solar Maximum Mission" in 1980, have shown that solar luminosity varies with solar activity during the n-year solar cycle. Researchers would like to extend the ACRIM record base begun in the 1980 as part of the Earth radiation budget database for the Global Change Research Program. They would especially like to avoid gaps between successive ACRIM missions to "connect" (calibrate) readings between successive instruments and facilitate detection of subtle changes.

In his proposal for launching a new ACRIM mission before the mid-1990s,[1] Richard C. Willson, of the Jet Propulsion Laboratory, cites estimates that all the climate variations known to have occurred in the past, from major ice ages to global tropical conditions, could be produced by systematic solar variability of as little as 0.5 percent per century. Because the results of many solar irradiance experiments would be required to monitor the solar luminosity for 100 years, the relative precision of successive experiments would have to be small compared to O.5 percent.

Researchers have adopted an overlap strategy that would deploy successive ACRIM experiments so that overlapping observation periods of approximately 1 year can be used to provide relative calibration of the data at a precision level (0.00l% of the total irradiance) that is substantially smaller than their inherent uncertainty (0.1%). Although continuous data on solar luminosity has not existed long enough to detect the presence of sustained solar luminosity changes that might have climate implications, the long-term precision required to detect such a trend would considerably exceed 0.1 percent.

[1] NASA plans to fly ACRIM on EOS flights starting around the year 2002, but a potential gap in measurements exists for the approximate period of 1994-2002. The only ACRIM sensor now in orbit is on UARS, a satellite whose useful life is expected to end In 1994. UARS might exceed Its design life, but recent problems with its battery power supplies also serve as a reminder that satellites can suffer premature failure.

SOURCES: Office of Technology Assessment and Richard C. Willson, "Science Objective of an Active Cavity Radiometer Irradiance Monitor (ACRIM) Experiment on a Dedicated Small Satellite System," in Committee on Earth and Environmental Sciences (CEES) of the Federal Coordinating Council for Science, Engineering, and Technology, *Report* of the *Small Climate Satellites Workshop* (Washington, DC: Office of Science and Technology Policy, May 1992).

Box B-10-Climsat Sensor Summary

SAGE Ill (Stratospheric Gas and Aerosol Experiment): an Earth-limb scanning grating spectrometer that would be sensitive from t he ultraviolet to the near infrared. Yields profiles of tropospherc aerosols,O^3 NO_2,H_2O OCIO-most down to aloud tops. Instrument mass: 35 kg; Power (mean/peak): 10/45 watts; Estimated Cost: $34 million for 3 EOS copies ($18M + $8M + $8 M).

EOSP (Earth Observing Scanning Polarimeter): global maps of radiance and polarization; 12 bands from near UV to near IR. Yields information on aerosol optical depth (a measure of aerosol abundance), particle size and refractive index, cloud optical depth and particle size, and surface reflectance and polarization. Instrument mass: 19 kg; Power (mean/peak): 15/22 watts; Estimated Cost: $28 million for 3 EOS copies ($16M + $6M + $6M).

MINT (Michelson Interferometer): Infrared measurements between 6 and 40 microns. Yields cloud temperature, optical depth, particle size and phase, temperature, water vapor, and ozone profiles and surface emissivity. Instrument mass: 20 kg; Power (mean/peak): 14/22 watts; Estimated Cost: $15-$20 million for first copy.

SOURCE: J. Hansen, W. Rossow, and 1. Fung, "Long-Twin Monitoring of Global Climate Forcings and Feedbacks," Proceedings of a Workshop held at NASA Goddard Institute for Space Studies, Feb. 3-4,1992.

size). Characterization of clouds and aerosols is necessary for both climate models and to interpret signals received by satellite from the Earth's surface (e.g., by AVHRR and Landsat). For example, aerosols affect the transmission of electromagnetic radiation through the atmosphere and the clouds, but they are currently among the most uncertain of global climate forcings. Cloud cover and aerosol content are highly variable; like SAGE III, the argument for launching these instruments as part of Climsat, rather than EOS, is the additional coverage and better sampling of diurnal variations.

MINT (Michelson Interferometer) is the only Climsat instrument that is currently not scheduled for inclusion in EOS. MINT would measure the infrared emission from the Earth at high spectral resolution over a broad spectral range. Its principal measurement objectives include cloud temperature, transrnissivity, particle size and phase (water or ice); temperature, water vapor, and ozone vertical profiles; and surface emissivity.

| Developing Advanced Systems for Remote Sensing

The final section of this appendix draws on comments by participants at an OTA workshop on the future of remote sensing technology and briefings from scientists at NASA, DOE national laboratories, and industry.

NASA has identified a variety of high-priority technologies needed to enable or enhance future space science missions, including EOS and the Mission to Planet Earth (box B-1 1). NASA's most urgent short-term technology requirements are for more sensitive long-wave infrared detectors, reliable cryogenic cooling systems, and development of submillirneter and terahertz microwave technologies. Mid-term requirements include new lasers, improved onboard data storage systems, and development of larger antenna structures. Long-term requirements, which are considered very important for the success of MTPE, include improvements in software and data analysis and in power systems. Improvements in software and data analysis are critical **to the success of EOS because scientists need to convert the raw data to information. Accumulating data is not equivalent to solving problems.**

Participants of OTA'S workshop on the future of remote sensing technology generally agreed that existing and planned efforts in technology development at the component level were sufficient to develop next-generation sensors. However, several participants expressed concern about the lack of commitment and funds to perform required engineering, integration, and prototyping of integrated, space-qualified sensors. This work is essential if the size, weight, and cost of space-based sensors is to decrease. Such efforts are particularly important for the large EOS "facility" instruments that were deferred or canceled-LAWS, SAR, and HIRIS. (One participant characterized the kind of development work that is necessary to develop

Box B-11–Technology For Mission To Planet Earth

Direct Detectors

The particular need is for detectors capable of monitoring the interaction of the long-wave infrared thermal emission from the Earth with greenhouse gases-this requires detection of far-infrared photons in the 8 to 20 micron range.

Cryogenic Systems

Cryogenic coolers are needed to increase the sensitivity of infrared radiation detectors, particularly at long wavelengths. Stored cryogens (e.g., liquid nitrogen) are not suitable for long-duration missions. Passive radiative coolers, which area mature technology, cannot be employed when extremely low temperatures are required or when there are geometric limitations (a passive cooler requires a large surface that never absorbs energy from the sun).

Mechanical cryo-coolers are miniature refrigerators. NASA plans to use tens of mechanical coolers during the 15-year EOS program. Concerns about their use include: their long-term reliability in a space environment; how to damp vibrations (NASA currently favors employing two matched cryo-coolers in a configuration where the vibrations of one cancel the other's); how to increase the efficiency of coolers (to provide sufficient cooling power); and how to reduce the cost of developing space-qualified units, which is currently measured in the million dollar range.

Submillimeter and Terahertz Microwave Technologies

The millimeter, sub-millimater (frequencies above 300 GHz) and terahertz region of the microwave is of interest because this is the region where small, light molecules and free radicals of fundamental importance in t he chemistry of the upper atmosphere can be monitored via their strong rotational emissions. Monitoring in this region also complements other techniques. For example, measurements taken with millimeter/sub-millimeter techniques are not affected by changes in aerosol or dust concentrations in the atmosphere (because the wavelengths are larger than the dust or aerosol particle size). In contrast, optical or ultraviolet measurements are strongly affected by aerosol and dust loading and therefore are sensitive to changes that resulted from the eruption of Mt. Pinatubo. Using techniques that are common to ground-based radio astronomy, researchers can analyze the strength and spectral width of molecular line shapes to determine the altitude and temperature distribution of molecules and radicals such as CIO, water vapor, nitrous oxide **(N_20), CO,** and $H0_2$.[1]

Historically, sources and detectors for this region of the electromagnetic spectrum have been notoriously difficult to develop. At lower frequencies, up through the millimeter wave region, conventional klystrons and multiplication techniques may be used. Optically pumped far-infrared lasers provide a source of energy at higher frequencies, but only at a relatively few discrete laser frequencies.

Lasers

As noted earlier, development of a space-qualified high-power laser would allow the measurement of global wind velocities. it would also be a powerful method to identify and measure concentrations and vertical profiles

[1] Molecules are "excited" to higher energy states following collisions with other gas species. Emission of energy occurs when the molecule "relaxes" back to its normal energy state. The strength of the emission is a function of molecular abundance. In addition, because of "pressure broadening," the spectral width of the emission contains information on the altitude distribution of the emitting molecule (pressure broadening occurs for molecules of Interest at altitudes at pressures corresponding to altitudes below 70 km). See, for example, Alan Parrish, "Millimeter-wave Environmental Remote Sensing of Earth's Atmosphere," *Microwave Journal, vol. 35, No* **12, Dec. 1992, pp. 24-34.**

of trace gases in the troposphere and stratosphere. In addition, it would allow accurate global measurements of altitudes and land surface elevations from space. Current research centers on the demonstration of reliability of CO_2 gas lasers and development of alternative solid-state lasers. Solid-state lasers require a laser "pump" to excite the upper energy level involved in laser action. Current research is focused on the development of diode-laser pumps because of their inherent reliability and energy efficiency.

LAWS is an example of a lidar (light detection and ranging, i.e., laser-based radar). New lasers are needed for lidars and for DIAL (differential absorption lidar). Important molecular atmospheric species such as oxygen, water, and trace species such as nitric oxide (NO) and the hydroxyl radical (OH) can be measured with great sensitivity using DIAL. Atmospheric temperatures and pressure can also be determined from an analysis of the molecular absorption line width and strength. Laser measurements of molecular absorption bands for species require tunable sources with extremely high frequency stability. For global use, systems must also operate at eye-safe levels or in eye-safe spectral regions. As mentioned earlier, laser velocimetry can be performed using either coherent or novel incoherent techniques. All of these issues are being explored in very active programs at DOE and NASA laboratories.

Onboard Data Storage Systems

EOS spacecraft will acquire enormous quantities of data. Onboard storage is necessary to manage these data-either to store data until satellite downlinks to Earth ground stations are available later in the orbit, or to facilitate data manipulation/compression to lower the required communication data rate to Earth. For example, the EOS AM-1 platform will acquire data at some 100 million bits/second (peak) and 16 million bits/second (average). Output of data at peak rates up to 150 million bits/second will occur when AM-1 is in contact with the TDRS satellite communications relay.

Near-term plans call for digital tape recorders to be used in EOS; however, the requirements of EOS spacecraft will push the limits of tape recorder technology. Current research is focused on developing alternative space-qualified storage systems, which would be smaller, lighter, more reliable (tape recorders have many moving parts), and better matched to the data requirements. Concepts under development include solid-state memories and optical disk technology.

Large Antenna Structures

Large lightweight antennas would facilitate development of affordable SARS.

Improvements in Software and Data Analysis

If current plans continue, the fully deployed EOS system of polar orbiters and other spacecraft are expected to acquire some 1-2 trillion bits of data each day. Storing these data and translating them into useful information in a timely manner is critical to the success of EOS. The SEASAT spacecraft (which included a SAR) operated for only three months in 1978, but scientists took eight years to analyze the data. A sizable fraction of the total EOS cost (currently at $8 billion for this decade) is earmarked to solving the myriad of problems associated with data acquisition, analysis, and dissemination. OTA plans to publish a report on EOS data issues in late 1993.

Power Systems

Development of lighter weight and more energetic power systems would have a number of applications. In particular, when combined with lightweight, large antenna structures, the possibility exists for placing radar systems in higher orbits. Ultimately, researchers would like to place systems in gee-stationary orbit. Large antennas would be needed because the beam size on the Earth is inversely proportional to antenna size.

SOURCE: OTA and Robert Rosen and Gordon 1. Johnston, "Advanced Technologies to Support Earth Orbiting Systems," paper IAF-92-0751, presented at the 43rd Cong. of the International Astronautical Federation, Aug. 25-Sept. 5, 1992, Washington, DC.

Box B-12–ARPA Space Technology Initiatives in Remote Sensing

ARPA's Advanced Systems Technology Office has proposed several advanced technology demonstration (ATDs) that might point to remedies for key problems in the development of future space systems: lack of affordability, long development times, and high technical risk. ARPA program managers note that "our current practice is to custom-build large satellites on roughly 10-year cycles. To avoid unacceptable program risk, only proven or space-qualified technologies are typically incorporated. These technologies become obsolete even before the first satellite is launched ..."

Two ARPA ATDs have particular interest to the civilian remote sensing community: the Advanced Technology Standard Satellite Bus (ATSSB) and the Collaboration on Advanced Multispectral Earth Observation (CAMEO). ATSSB would be characterized by very high payload mass fraction and a simplified payload interface ("bolt-on") that would support a wide variety of missions while minimizing acquisition times and recurring costs. CAMEO is a proposal for a joint DoD/DOE/NASA collaboration to design, build, and launch a satellite using ATSSB that would carry instruments of interest to both civil and military users.

CAMEO would demonstrate the utility of smaller satellites to rapidly insert technology and shorten development time for larger satellites. It would carry three instruments:

- CERES, a NASA-developed instrument for aloud and Earth radiation budget measurements. CERES is an approved EOS instrument scheduled for launch in the late 1990s. Earlier versions of the CAMEO proposal considered a higher performance, but unproved, las Alamos-designed radiometer.
- MPIR, a DOE-developed, very wide-field of view (90 degrees; swath width at nadir for nominal orbit altitude of 700 km is 1,000 km), pushbroom multispectral imaging radiometer. MPIR's principal objective would be to gather data for global change research, primarily aloud properties (e.g., cloud detection, identification, type, amount height, reflectance, optical thickness, and internal characteristics such as particle size and phase). Its 10 spectral bands would measure reflected sunlight and thermal emission from the Earth at visible/near-infrared to long-wave infrared wavelengths from 0.55-12 microns. Because MPIR's primary mission is measurement of cloud properties, high resolution is not necessary. The baseline proposal calls for a ground resolution of 2 km at nadir. MPIR would cool its medium-wave and long-wave infrared detectors to 60 K with an 600-milliwatt Stirling-cycle mechanical cooler. MPIR would be small (it would fit in a box 20 cm X 20 cm X 36 cm) and lightweight (25 kg). Its size and weight would also make it suitable for a flight on a UAV.

lasers for LAWS and SAR as "somewhere between exploratory and advanced development.")

Several researchers interviewed by OTA believed the lack of attention to engineering development was symptomatic of a larger problem: government interest and investment typically wane as a technology becomes more mature. However, schedule slips and cost overruns that occur during the final stages of instrument/platform development might be avoided by making a greater investment earlier in the development cycle, even if it is for what maybe perceived as lower priority engineering problems.

Currently, the time required between preliminary design and launch for a new, large, and complex satellite system may stretch to nearly a decade. Workshop participants agreed unanimously that this period must be reduced for remote sensing systems. Similarly, workshop participants stressed the importance of reducing space mission costs. Unfortunately, the space community has not reached consensus on how best to achieve these goals. Box B-12 discusses ARPA's belief that space missions can be carried out with lower costs and shortened acquisition times by developing small satellites that would employ a small common satellite bus featuring standardized payload-bus interfaces. In particular, ARPA has proposed a joint collaboration among NASA, DOE, and ARPA to build and fly a gap-filling satellite to collect data for Earth radiation budget experiments. This satellite would also demonstrate technology applicable to

- LMIS, a DARPA-sponsored narrow field-of-view, high-resolution multispectral imager. LMIS would use pushbroom image formation and have a mechanically cooled focal plane. Notable among its characteristics is its hyperspectral imaging (32 bands) in visible/near-infrared bands. Other spectral bands would image the Earth in visible, short-, and medium-wave infrared. Resolutions would range from 2.5 meters in the panchromatic band to 20 meters in the medium-wave infrared. LMIS' swath width at nadir would be 20 km.

CAMEO's flight of CERES would avoid a likely gap in Earth radiation budget measurements while LMIS and ATSSB would demonstrate technologies for advanced imaging satellites. In particular, ARPA hopes LMIS and ATSSB would facilitate follow-ons in the Landsat series that would be lighter, smaller, less expensive, and incorporate a greater number of spectral bands. However, realizing all of these objectives in an imaging system similar to Landsat is likely to prove difficult, even if the CAMEO demonstration proved successful. For example, although the Thematic Mapper on Landsat 6 and Landsat 7 have fewer bands and somewhat lower ground resolution than proposed for LMIS, they also have a much larger swath width (165 km versus LMIS' 20 km). Whether it will possible to develop a LMIS-type instrument with a wider field-of-view is one of many technical challenges. An ancillary issue t hat affects CAMEO and other proposed multispectral and hyperspectral imaging satellites is how best to use the added spectral information. Researchers in the satellite-based HIRIS program and in the aircraft-based HYDICE program are still at a relatively early stage in determining the capabilities of hyperspectral imaging.

ARPA's ATDs were fully supported by the DoD, but were severely cut by the Senate Appropriations Defense Subcommittee staff. The programs have been restructured for a fiscal year 1994 start and include an added new emphasis on the potential benefits of CAMEO in enabling the United States to develop and greatly expand its role in future commercial remote sensing markets.

SOURCE: Advanced Research Projects Agency, 1993.

follow-ons in the Landsat series and to global change research. Other proposals for small satellites and lightweight remote sensing instruments have been advanced by the DOE national laboratories (box B-13).

In an era of level or declining budgets, cost, not technology, may be the most important factor in determining which new remote sensing projects to fund.[74] **However, even without the pressure induced by recent budget cutbacks, programs that hope to address the fundamental questions associated with global change research in a timely manner will still have to evolve in the direction of "smaller, faster, better, cheaper."** Shorter project development periods and lower costs would better match the period over which scientific understanding improves, technology advances, and changes occur in the Earth systems under study.

As noted in chapter 2, the projected annual shortfall between NASA's planned activities and appropriations may increase throughout the decade. With multibillion dollar shortfalls, new development efforts for remote sensing technologies may be curtailed in an effort to maintain ongoing programs. Given this reality, one OTA Advisory Panel member suggested that NASA should institute a process to phase out approximately 15 percent of the base program per year to make room for innovation and new scientific/technical directions. This panel member further noted that because the current management approach is to key new ideas to budget appropriations, "new ideas rarely see the light of day. '

Other researchers interviewed by OTA agreed that lack of funding for some programs might stifle future innovation in the future, but disagreed with the assessment that a problem currently exists. They

74 This view is widely held; see, for example, Dean Freer, ''Using Today's Strategic Defense Initiative (SDI) Technologies to Accomplish Tomorrow's Low Cost Space Missions, " IAF-92-0752, paper presented at 43rd World Space Congress, Aug. 31, 1992, Washington, D.C.

Box B-13-DOE Multispectral and Hyperspectral Imaging Systems

The Department of Energy is developing a variety of multispectral instruments for launch on small satellites to support ongoing efforts in global change research and to demonstrate technologies for nuclear proliferation monitoring. DOE's multispectral pushbroom imaging radiometer-MPIR-was discussed in box B-12. This box summarizes characteristics of two other proposed DOE instruments: SiMS-small imaging multispectral spectrometer (formerly denoted as "mini-HIRIS") and the MT1-multispectral thermal imager.

The SIMS spectrometer is a joint NASA-DOE technology project to demonstrate that a small, lightweight instrument can obtain high spectral resolution images of modest spatial resolution that would be useful for global change research and non-proliferation missions. SIMS would have two grating spectrometers. It would operate in 5 nm contiguous bands from 0.4-1 micron and from 1-2.5 micron. SIMS would employ a 10 cm diameter telescope; its spatial resolution in the various bands would be 80-100 meters from its nominal orbit altitude of 700 km.[1] AS noted in earlier discussions of HIRIS, hyperspectral imaging with even modest spatial resolution can translate into enormous data rate and storage requirements. A 20 km X 20 km SIMS image would contain some 100 trillion bits. Data rate and storage requirements can be reduced, however, by selecting only a small subset of spectral channels for each scene.

The Multispectral Thermal Imager (MTl) is, in effect, DOE's version of ARPA's LMIS instrument (box B-1 1). MTI is a technology demonstration that is jointly sponsored by DOE's Sandia National Laboratory, Los Alamos National Laboratory, and Savannah River Technology Center. Its objectives are to collect high spatial resolution multi-spectral and thermal images for proliferation monitoring and to demonstrate technology applicable for future Landsats. However, in contrast to ARPA's proposal for CAMEO, MTI's development will not be tied to the development of a new standardized bus.

MTI would operate from 0.4-12 microns in 18 spectral bands. The instrument would fly in a nominal orbit altitude of 500 km with a 0.35 meter diameter telescope. Its spatial resolution would range from 5 meters in the 0.4-1 micron (VNIR) to 40 meters in the 8-12 micron band (LWIR). A separate linear array would be used for each spectral channel on a common focal plane assembly that would be cooled to 80 K with Stirling-cycle mechanical coolers.

noted, for example, that innovation and new scientific or technical directions have emerged out of existing efforts by several agencies, notably in the discovery and investigation of the Antarctic ozone hole. Furthermore, they believed that competitive peer review of grant proposals to agencies such as the National Science Foundation insured turnover in base programs.

Developing Follow-ons in Landsat Series

User requirements for surface remote sensing data can be grouped in four broad categories as shown in table B-3. The first grouping of requirements will be satisfied by the EOS system; the second grouping is satisfied by the current Landsat; and the third and fourth groupings might be satisfied by advanced Landsats.

Landsat 5 was launched in March 1984. It has greatly exceeded its planned operational life and will be replaced by LandSat 6 in late 1993. Landsat 6 is similar in most respects to Landsat 5, differing most noticeably in its incorporation of an enhanced Thematic Mapper (TM) (table 4-1). The enhanced features of Landsat 6 include the addition of a 15-meter panchromatic (black and white) band, which can be used as a ''sharpening' band for the 30-meter multispectral imagery and improved band-to-band registration (i.e., how well the same scene is recorded in different spectral bands). Landsat 7, scheduled for launch in the 4th quarter of 1997, would be the first

An example of a proliferation application for MTI **would be to detect, monitor, and characterize the thermal signature from a nuclear reactor's cooling pond. This requires an infrared detection system that has relatively high spatial resolution. Other applications are noted below.**

Nuclear Facility Monitoring Objectives

- **Relevant Objectives**
  - **detect/identify proliferators as early** in cycle as possible
  - -assess =capabilities: test or use?
- Production Reactor
  - -thermal power and duty cycle
  - -total burnup
  - -fuel cycle technology
- Nuclear Material Processing/Reprocessing Plant
  - -plant identification
  - -process type
  - -capacity
  - —throughput
- Enrichment Plant
  - -plant identification
  - -process identification and capacity
  - —throughput and duty cycle
- Nuclear Device Fabrication/Storage Facility
  - -facility identification
  - -material fabricated and duty cycle
  - —storage area identification and location

[1] Ireasing the resolution to 30 meters, the resolution of Landsat 5, would require increasing the aperture by approximately a factor of 10.

[2] SOURCE: Los Alamos National Laboratory, Space Science and Technology Division.

Landsat to incorporate stereo (table 4-2); it would also have higher resolution than Landsat 6.[75]

The first opportunity to depart from the current evolutionary approach to Landsat improvements will occur in Landsat 8, which, if approved, might be launched some five years after Landsat 7. Development of advanced Landsats presents familiar aspects of the debate over how to guarantee long-term continuity of measurements in an operational system, while still allowing for technical innovation. Because much of the value of Landsat for monitoring global change lies in its ability to collect comparable data over time, follow-on systems must either include existing spectral bands or provide a method to reconstruct older Landsat data in software. This is possible using existing technology. (This assumes that an examination of Landsat data concludes that the original bands chosen for Landsat are still the most useful for Earth observation. Another option would be to discard some bands and retain only the several that are considered most important for continuity).

A more contentious issue centers on sensor design for Landsat 8 and beyond. The design of Landsat's detectors requires compromises and tradeoffs among spatial, spectral, and radiometric resolutions. Competing sensor concepts differ in their choice of optics

[75] The High Resolution Multispectral Stereo Imager (HRMSI), if funded, would have a ground resolution of 5 meters in the panchromatic band and 10-meter resolution in the new-infrared bands, This is a three-fold improvement over Landsat 6. The Enhanced Thematic Mapper (ETM+) planned for Landsat *7* also incorporates some improvements over the ETM for Landsat 6.

Table B-3-Surface Data Requirements

1. Wide-field, low-moderate spatial resolution
. Global land survey
. Global ocean survey
2. Medium-field, moderate-high spatial resolution
. Synoptic regional coverage
• **Landsat user commmunity**
3. Narrow-field, high spatial resolution, stereo
• **Terrain elevation**
• **Perspective views, flight simulation**
4. Narrow-field, high spatial and spectral resolution
• Custom-tailored data acquisition
. Application specific

SOURCE: A.M. Mike and C. F. schueler, "Landsat Sensor Technology," Briefing to OTA at Hughes Santa Barbara Research Center, January 1992.

(narrow or wide-field), scanning approach, and detector focal plane. Figure B-4 depicts the different approaches (note, direction of satellite is indicated by large arrow).

The simplest detector concept is to use a single detector for each spectral band. This is the approach used in NOAA's AVHRR. Landsat uses several detectors per band along the satellite track and scans these detectors (using a mirror) simultaneously across the satellite track. The scan rate is relatively high, but still much slower than if only a single detector had been used. NASA used this type of detector on the multispectral sensor (MSS) on Landsat 1-5, and also on the Thematic Mapper on Landsat 4 and Landsat 5. It will also be used on the enhanced TM on Landsat 6.

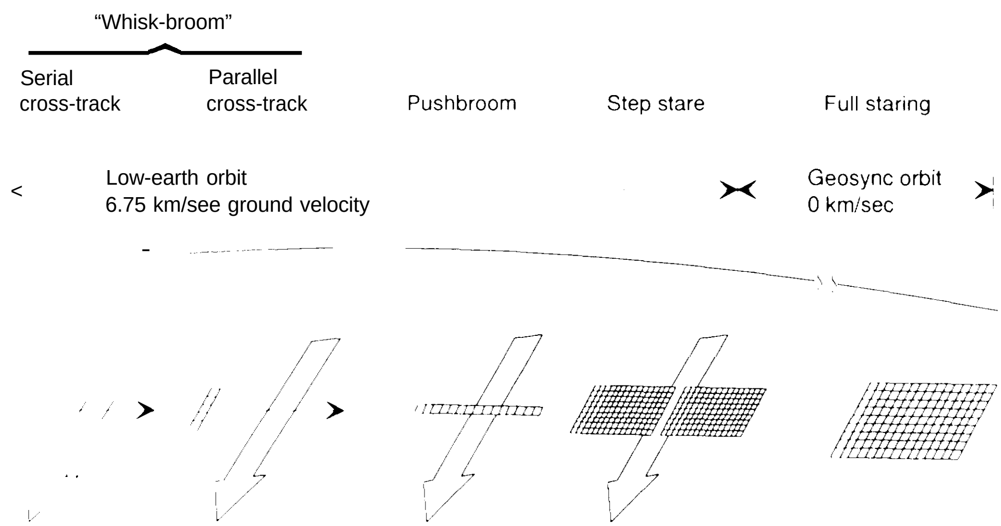
A simple detector array has several advantages. In particular, calibration of the sensor is relatively easy because only a few electronic channels need to be compared, and optics with a narrow field-of-view may be used because they image only across a short array. The principal disadvantage of this detection scheme is its limited ''dwell time' (the time the detector is gathering signal from a particular location on the Earth). The limited dwell time restricts the signal-to-noise ratio at the detector and also requires ''fast' detectors and associated electronics (i.e., detectors and electronics with high temporal frequency response). Small detector arrays also require scanning mirrors. While scanning mirrors have proved robust, a system without a mechanical seaming system would be more reliable and come closer to the ideal of a detector that had only small numbers of electronic components and no moving parts.

The "pushbroom" detector concept, which has already been demonstrated on SPOT and on JERS-1, has been proposed for future Landsats. In the pushbroom concept, wide-field optics image a one-dimensional line image of the Earth onto a large linear array of detectors. The motion of the pushbroom along the satellite track generates a series of one-dimensional images, which are then added together electronically to form a two-dimensional image. Several advantages follow, principally that the scan rate is now slowed down (to that provided by the motion of the satellite moving in orbit+ .75 km/s for a satellite in orbit at 700 km). This greatly increases the time the detector "sees" the image, which results in a larger signal and therefore allows either greater spatial resolution or finer spectral resolution. The pushbroom concept also allows designers to craft a smaller, lighter instrument. Finally, the reliability of the pushbroom should be high because it doesn't use mechanical cross-track scanning,

The pushbroom design has two principal drawbacks. First, it requires much longer detector arrays, which have many more elements and are therefore more difficult and expensive to manufacture and calibrate (the number of detector elements for pushbroom linear arrays might number on the order of 10,000). Second, it requires optics with a wide field-of-view to obtain the same swath width as for the corresponding seamer. Pushbrooms were not chosen for Landsat 7 because the requirement for a 185 km swath width would have forced designers to use wide field-of-view optics. The SPOT satellite, which uses a pushbroom, avoids some of the difficulties of developing wide-field optics because its swath width is only 60 kilometers.

Pushbroom scanners are being considered for Landsat 8. A more ambitious proposal would replace the linear detector array of the pushbroom with a large two-dimensional detector array and use a' step-stare' imaging scheme. A step-stare system would use image motion compensation to allow the array to stare at a particular patch on the ground as the satellite moves forward. The array would then be stepped to a new location and held again until it had imaged all the way across track. The advantages of this system are increased dwell time and necessity for only moderate

Figure B-4-Surface Optical Remote Sensing Techniques



Focal plane	Single detector per band	Multiple detectors per band	Linear array for each band	Two-dimensional array for each band	Two-dimensional array for each band
Application example	AVHRR SEAWIFS	MSS TM	SPOT JERS, MOS		SDI trackers, missile seekers
Cross-track **scan** speed	High	Medium	Zero	Medium	Zero
Motion	Continuous	Oscillatory	None	Discontinuous	None

SOURCE: Hughes Santa Barbara Research Center Briefing Charts, 1992.

field-of-view optics. Its disadvantages are a larger and more complex focal plane than the pushbroom, which leads to greater problems in manufacturing, calibration and higher cost. Active mechanical cooling is also likely to be necessary to cool the array (passive radiative cooling may be possible for pushbroom detectors). The discontinuous motion also presents problems—the system has to settle between each step. A last option, which is not appropriate for Landsat, is a full stare system. Satellite velocities in low-Earth orbit are too fast to allow a full stare system to dwell long enough on a region of interest. Full stare systems could be used in geosynchronous orbits.

As noted at the beginning of this appendix, the risks in developing a new sensor system have two components: the technical maturity of component technologies and the design maturity. A particular design that has not been used before may be a relatively risky venture for an operational program, even if it is based on proven technology. Some concepts for advanced Landsats would stress both component maturity and design maturity.

A notable example of a new component technology that might enable the design of smaller, lighter, and less expensive land remote sensing instruments, with much greater spectral capabilities, is the linear spectral wedge filter, the heart of a proposed "Wedge Spectrometer. '[76] The wedge spectrometer, under development at Hughes Santa Barbara Research Center (SBRC), would be an extremely compact visible and infrared imaging spectrometer. A demonstration system has been fabricated; it uses a 1 cm^2 linear spectral wedge filter and detector array to gather a 128 X 128 pixel image in each of about 64 spectral bands in the visible/near-infrared region (0.4-0.85 microns) .[77] SBRC has tested this system on an aircraft under ARPA sponsorship and generated image products.

The compactness of the wedge spectrometer is achieved in part because spectral discrimination occurs in a focused beam. In contrast, imaging spectrometers that use gratings or prisms to disperse light require collimating and reimaging optical and mechanical components. The wedge spectrometer is also thought to be inherently cheaper and more rugged than grating or prism instruments. The key element of the system, the filter wedge, has been fabricated and is in use in devices such as laser warning receivers. However, the filter wedge in a laser warning receiver would not be suitable for calibrated remote sensing.

Officials at SBRC informed OTA of several spectral and radiometric performance issues that require further work so that a wedge spectrometer might be used in Earth remote sensing applications that require a high degree of radiometric and spectral sensitivity.[78] SBRC is currently under contract to the Defense Nuclear Agency to demonstrate the wedge spectrometer for treaty verification applications. SBRC expects to demonstrate the device operation in the short-wave infrared (SWIR) bands in calendar year 1993.[79]

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76 The key element of the Wedge Spectrometer is the linear spectral wedge filter; a thin-film optical device that transmits light at a center wavelength that is specified by the spatial position of illumination on the filter. (A thin film of oil selects light via a similar ''interference' effect and accounts for the familiar rainbow of colors that are seen from varying thicknesses of an oil slick. The wedge falter is, in effect, an interference filter with a thickness that varies linearly along one axis.) Therefore, if an array of detectors is placed behind the filter, each detector will encounter light from a scene at a different center wavelength. If there is a linear variation in wavelength versus spatial position, the array output is effectively the sampled spectrum of the scene. An array of detectors behind the falter will vary spatially in one direction and spectrally in a perpendicular direction. Scanning the falter/array assembly along the spectral dimension will build a 2-dimensional spatial image in each of the spectral bands transmitted by the filter.

77 The near-infrared is often defined as 0.4- 1.0 microns.

78 A major issue for the filter wedge 1s improving "out of band' performance---currently, energy at wavelengths other than at the center wavelength specified by the spatial position of illumination on the filter may be passed. This energy undergoes multiple reflections within the filter substrate and results in inaccuracies in spectral information. Grating or prism systems are immune from this problem.

79 The SWIR is often defined as 1.0-2.5 microns.